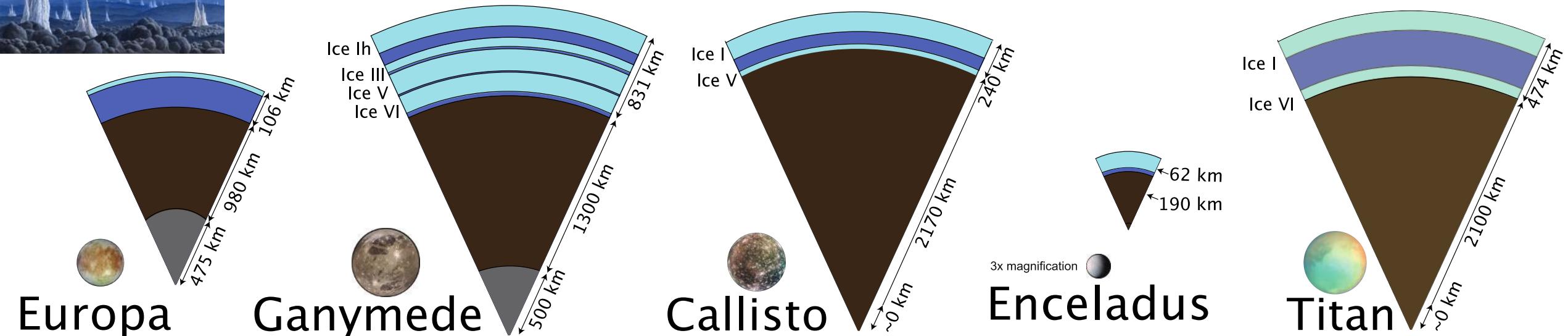
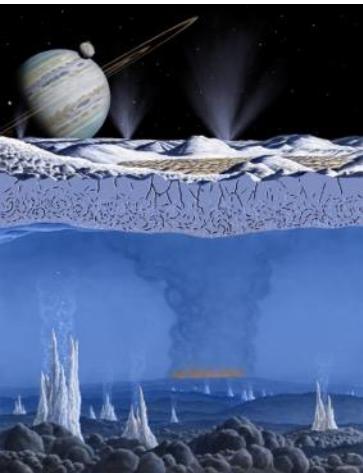


Deep Oceans in Large Icy Moons

Steve Vance (svance@jpl.nasa.gov),

Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, United States,



Introduction

- Deep oceans expand the parameter space of possible ocean properties
 - A broad range of P, T, and undetermined composition
 - Ocean and ice composition affect thermal properties, melting points.
 - These are being explored in the lab
- This will be important as new spacecraft measurements improve constraints on
 - composition, heat flow, density structure, etc...

	Mean Radius in km	Bulk Density in kg m ⁻³	Moment of Inertia (C/MR ²)	Inferred H ₂ O thickness in km	Rotation Period In hrs	Radiogenic Heat in GW	Tidal Dissipation in GW	Seismic Energy Release in GW (%)
Earth^a	6371	5514	0.3307	3.5	24	31,000	2636±16	22 (0.8)
Moon^{a,b}	1738	3340	0.3929 ±0.0009	n/a	672	420	1.36±0.19	6x10 ⁻⁷ (0.4x10 ⁻⁵)
Mars^c	3397	3933	0.3662 ±0.0017	n/a	24.6230	3,300	--	?
Europa^{d,e,f}	1565.0 ±8.0	2989 ±46	0.346 ±0.005	80-170	84.4	200	<10,000 >1000 (ocean) 1-10 (rock)	?
Ganymede^{e,f,g}	2631.17 ±1.7	1942.0 ±4.8	0.3115 ±0.0028	750-900	171.7	500	<50 >1 (ocean)	?
Callisto^{e,f}	2410.3 ±1.5	1834.4 ±3.4	0.3549 ±0.0042	350-450	400.5	400	<20 >4 (ocean)	?
Titan^{e,h,i}	2574.73 ±0.09	1879.8 ±0.2	0.3438 ±0.0005	500-700	382.7	400	<400 >11 (ocean)	?
Enceladus^{e,h,j}	252.1 ±0.1	1609 ±5	0.335	60-80	32.9	0.3	<20 >10 (ocean)	?

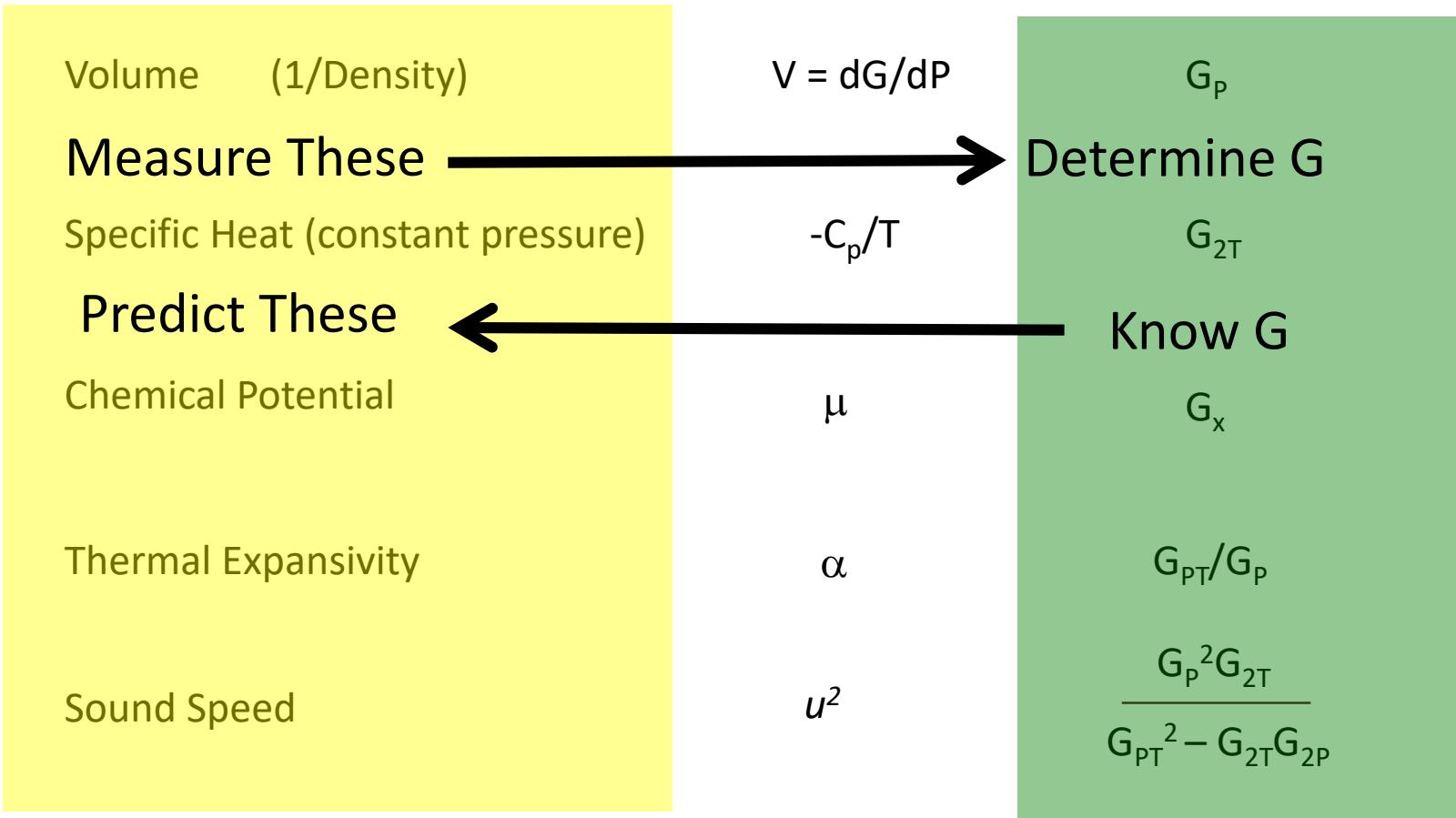
a) Williams et al., 2001 b) Goins et al., 1981; Williams et al., 1996; Siegler and Smekrar, 2014 c) Folkner et al., 1997, Nimmo and Faul, 2013 d) Tobie et al. 2003, Hussmann et al., 2006; Vance et al., 2007 e) Chen et al., 2014; Tyler, 2014 f) Schubert et al. 2004 g) Bland et al., 2015 h)

Exploring material properties



Gibbs Energy Derivatives

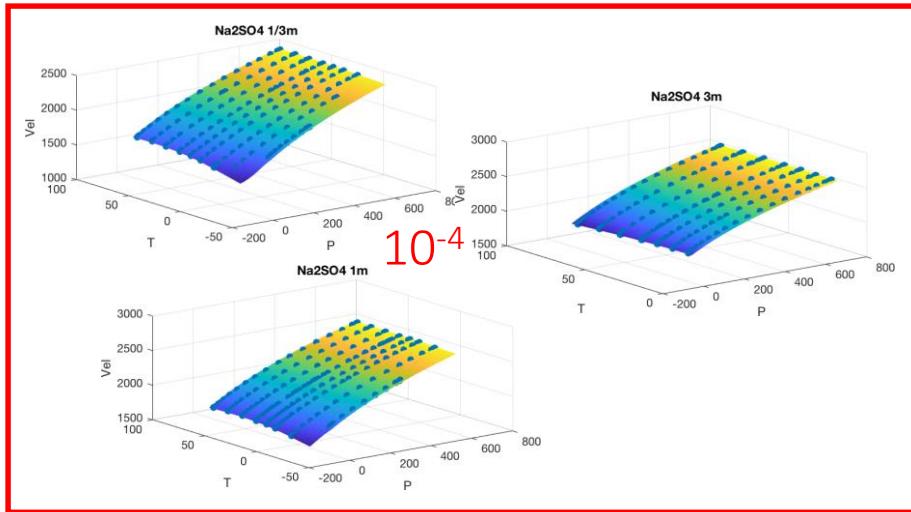
G is solution of an ODE



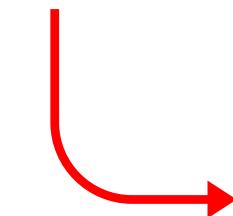
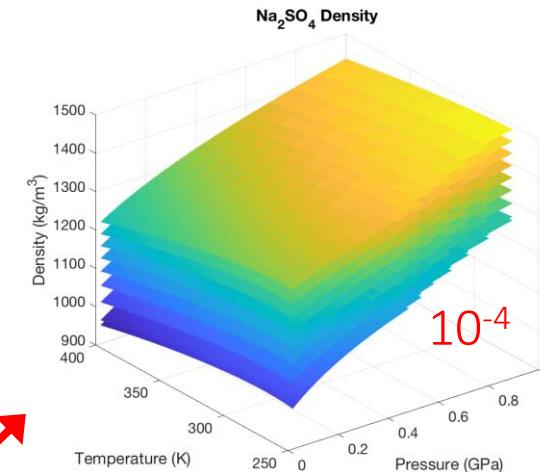
Gibbs energy at high pressure is accurately determined from sound speeds vs P, T, and X

Speed of sound: the Na-Mg-Cl-SO₄ brines

The Na-Mg-Cl-SO₄ brines

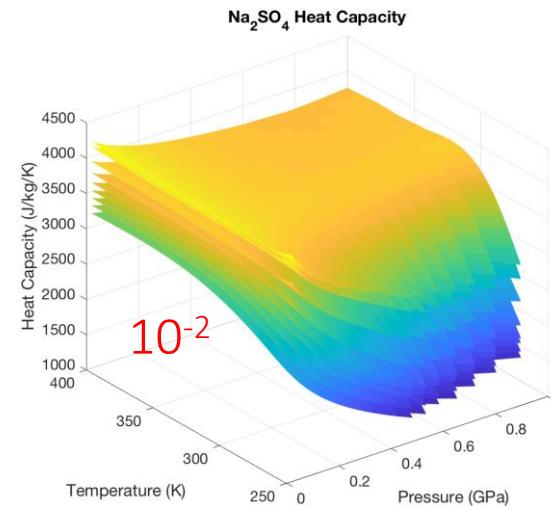
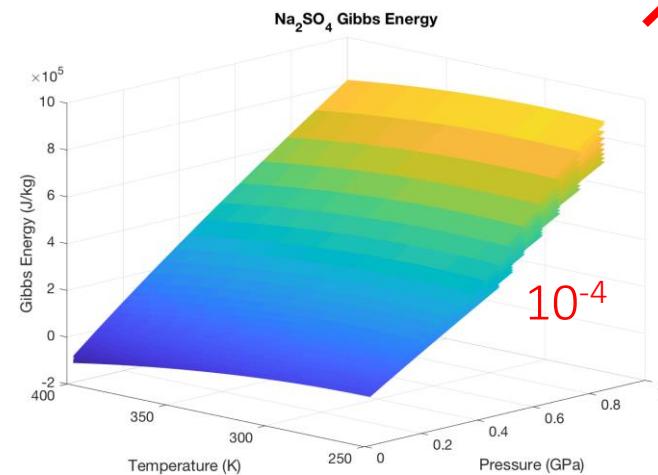


dG/dP

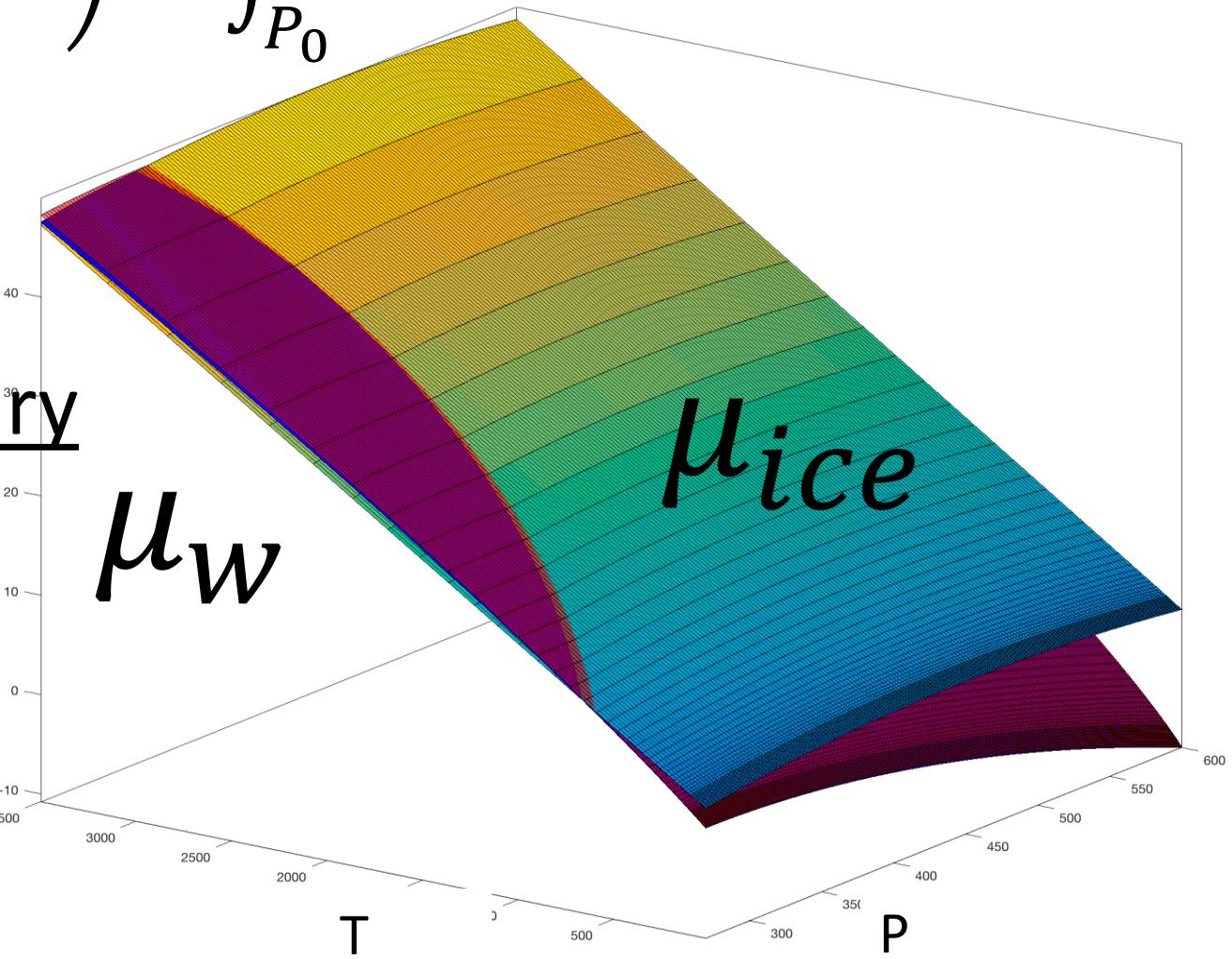
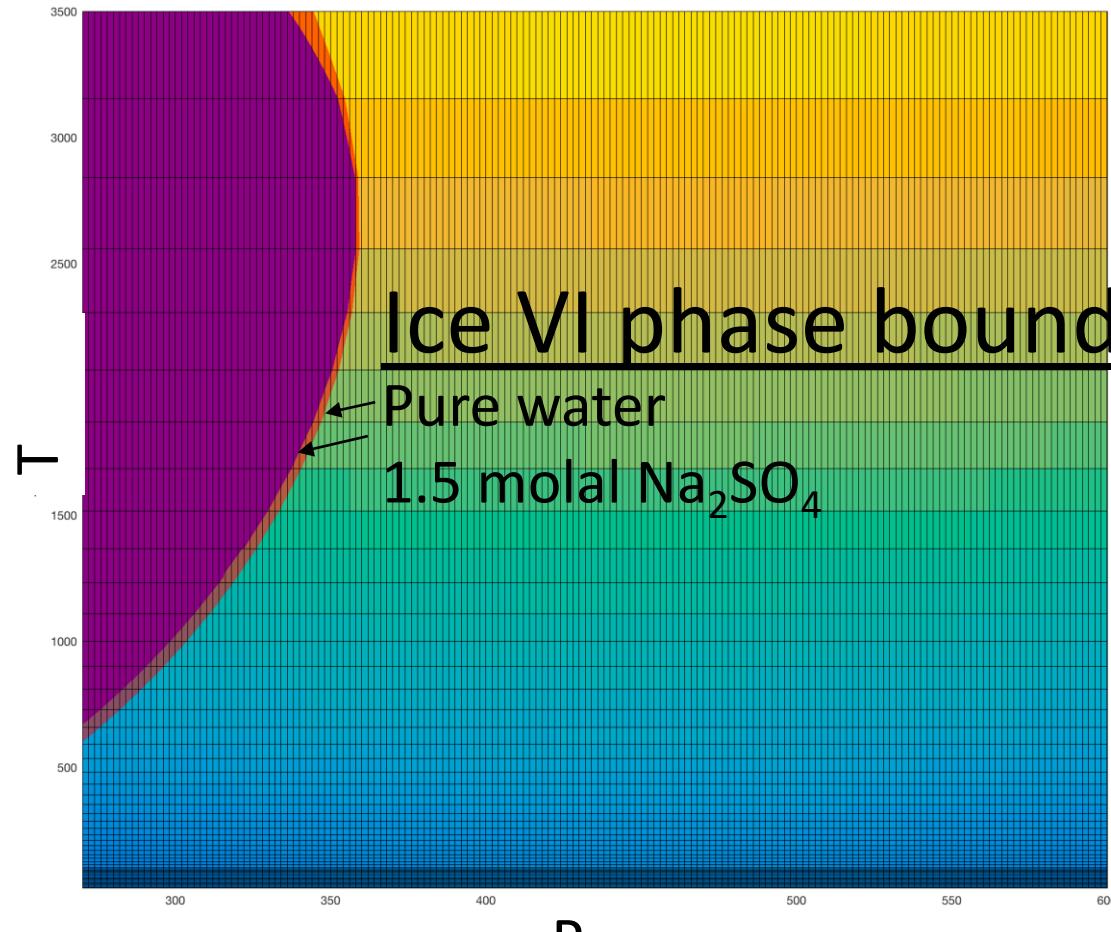


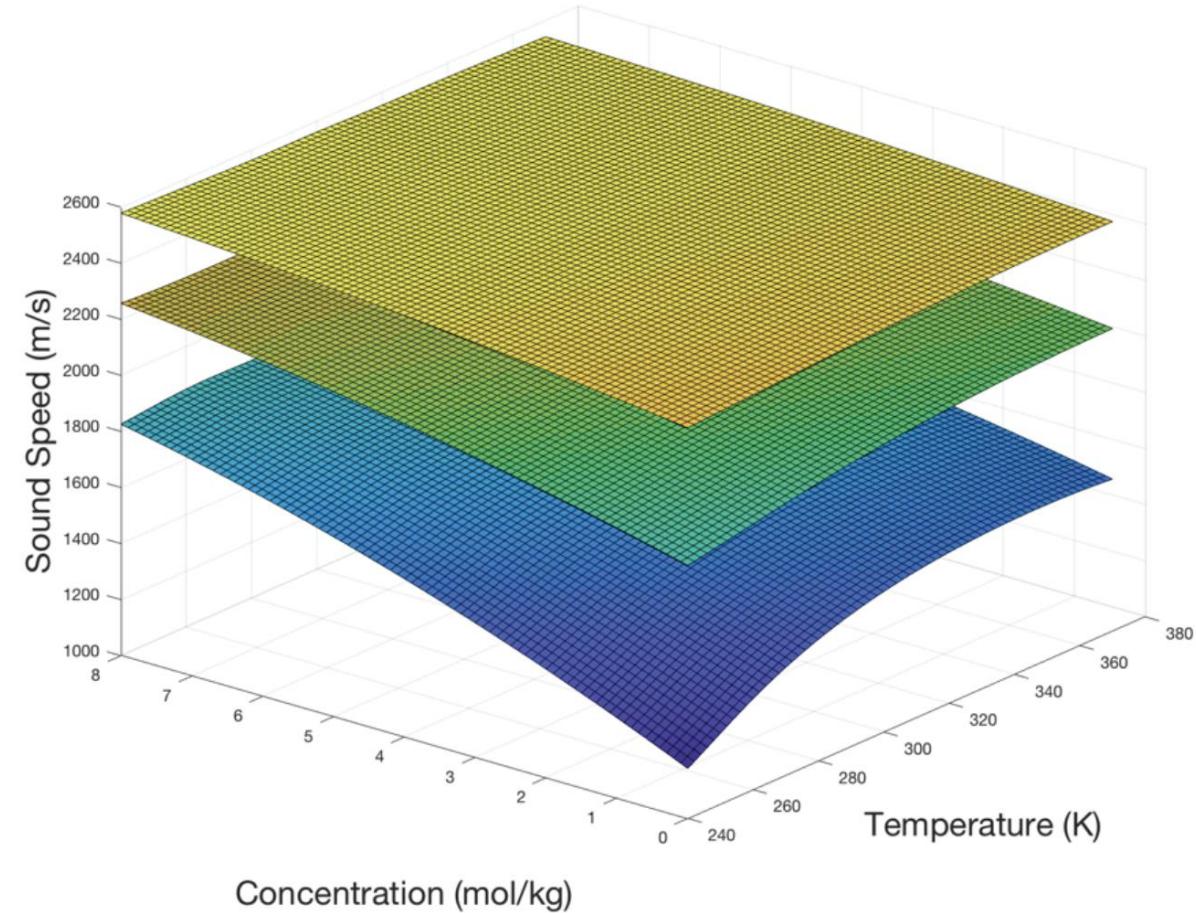
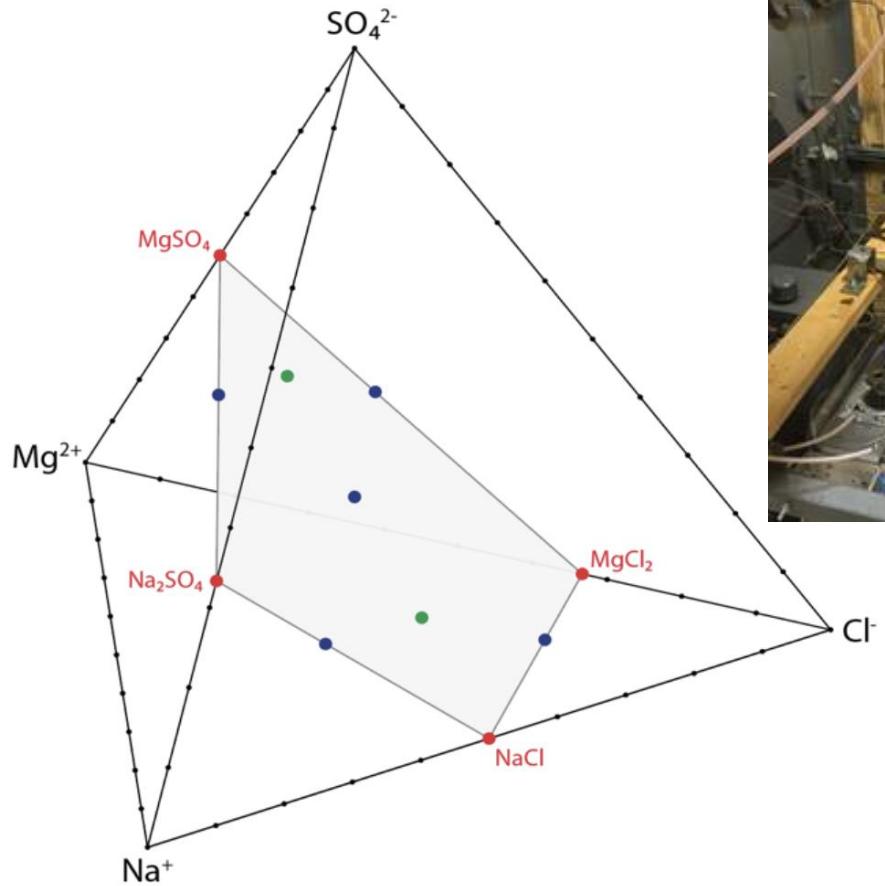
Integration
(PTX)

dG/dT



$$\mu(P, T,) = H^0(P_0, T_0) + \int_{T_0}^T C_P dT' - \\ T \left(S^0(P_0, T_0) + \int_{T_0}^T \frac{C_P}{T'} dT' \right) + \int_{P_0}^P V(P', T') dP'$$





With UW undergrad students Penny Espinoza, Jason Ott, Nathan Reinsdorf

American Journal of Science

NOVEMBER 2017

THE WATER-CARBON DIOXIDE MISCELLIBILITY SURFACE TO 450 °C AND 7 GPa

EVAN H. ABRAMSON[†], OLIVIER BOLLENGIER, and J. MICHAEL BROWN

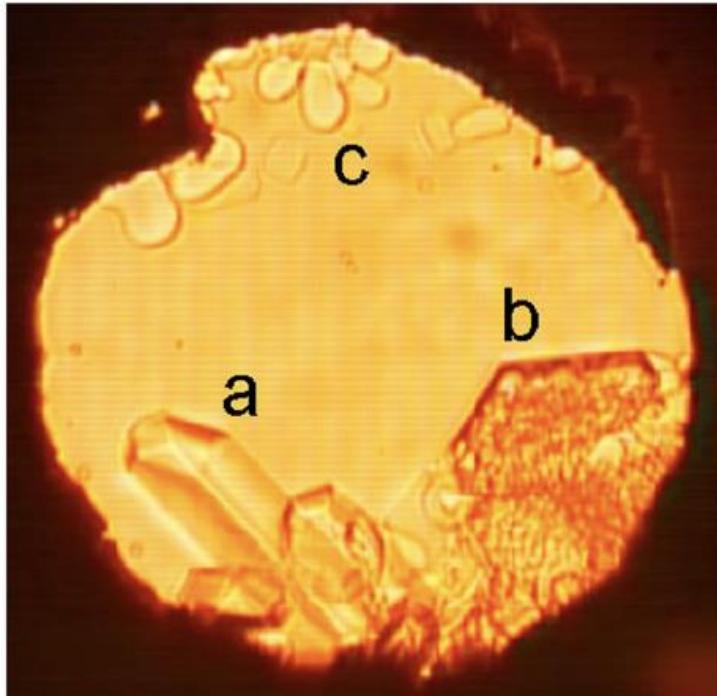
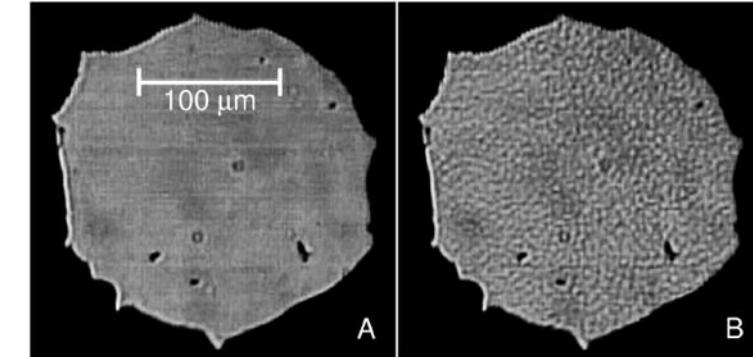


Figure 4. Photomicrograph of crystals growing from a water-CO₂ fluid at 240 °C and 6.5 GPa. Crystals “a” and “b” are both of phase S3 and were observed to fall through the fluid. At first “b” was clear, but then abruptly darkened, presumably as trapped fluid (non-stoichiometric relative to S3) precipitated crystallites of the H₂O(VII)-S3 eutectic. Crystals “c” are H₂O(VII) which floated up through the fluid.



SCIENTIFIC REPORTS

OPEN

Water-carbon dioxide solid phase equilibria at pressures above 4 GPa

E. H. Abramson , O. Bollengier & J. M. Brown



New JPL High-Pressure Facility

100,000 psi operating pressure

Designed and built with

Cal Poly Pomona Intern
Eduardo Salazar
and
JPL scientist Stewart Sherrit



Pressure Vessel

Harwood Engineering
SK-1544-C, 200 ksi



Hand Pump

Newport Scientific
46-12180-1, 40 ksi

X10 Pressure Intensifier

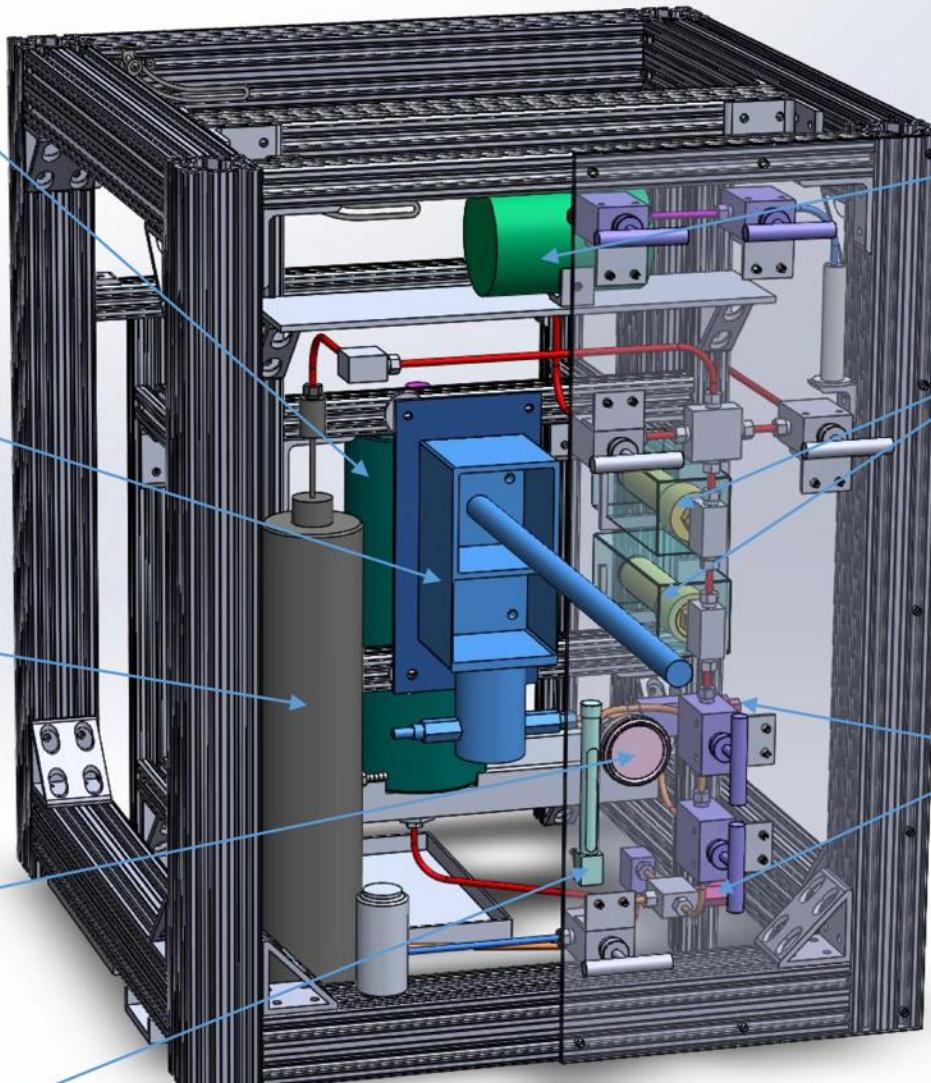
Harwood Engineering
B2.5, 100 ksi

10 ksi Gauge

Mcmaster carr
4053K18

Dead Volume Piston position Indicator

Mcmaster carr
1201K12



Optical Absorption Cell

Newport Scientific
41-11552, 100 ksi



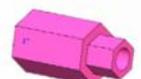
Pressure Transducers

Omega Engineering
PX91P0-200KSI, 200 ksi



Pressure Safety Head

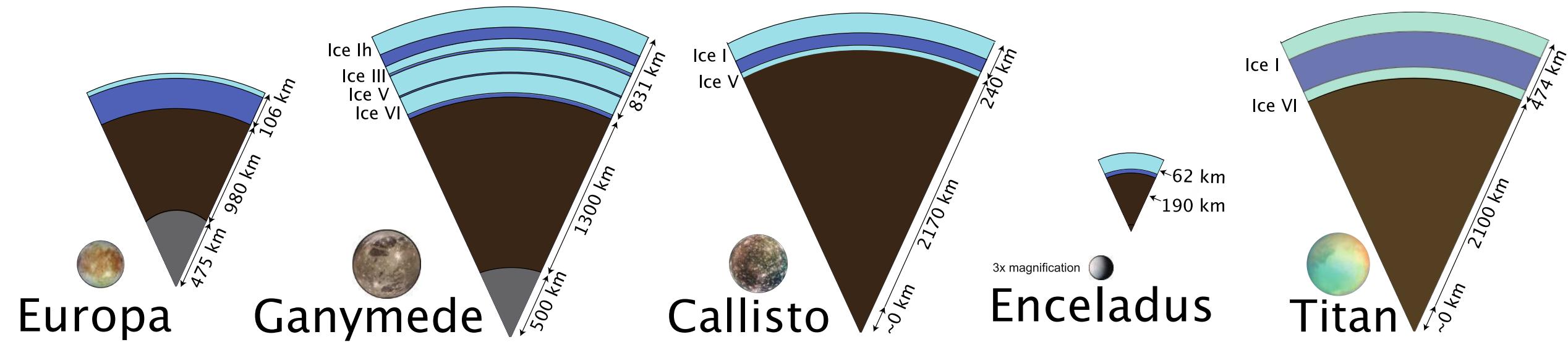
High Pressure Co. (HIP)
60-61HM4, 60 ksi,
11,500 psi rapture disk
plus 6% and minus 3% tolerance



Applications to deep oceans in icy moons

PlanetProfile: interior structures with self-consistent thermodynamics

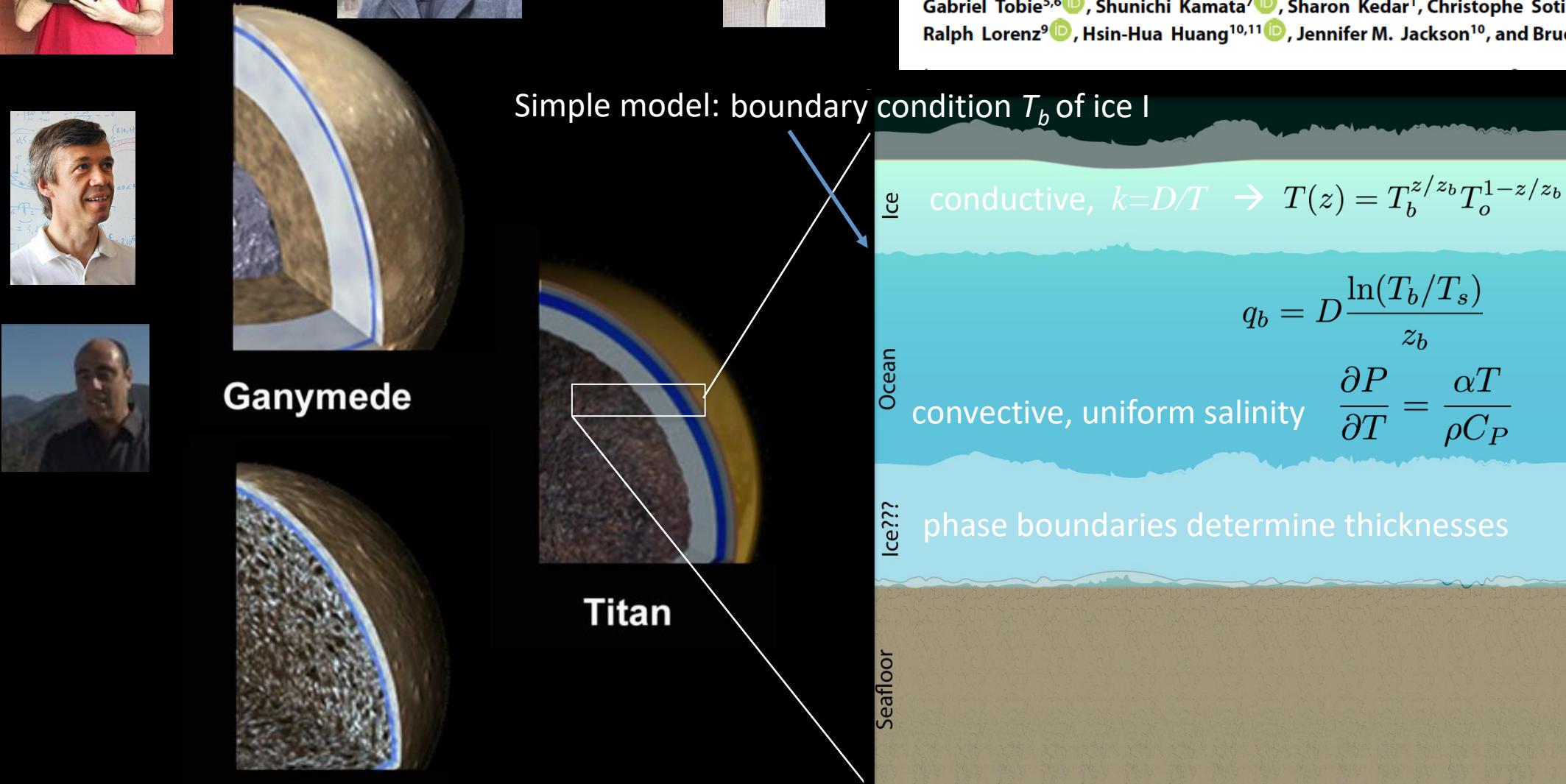
- accounts for the influence of ocean composition
- sets the stage for water-rock interaction modeling
- useful for geophysical inversion

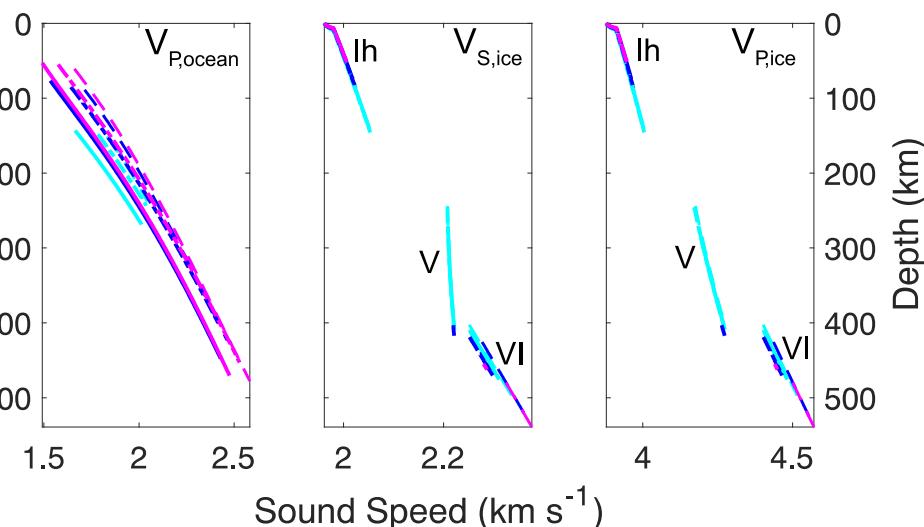
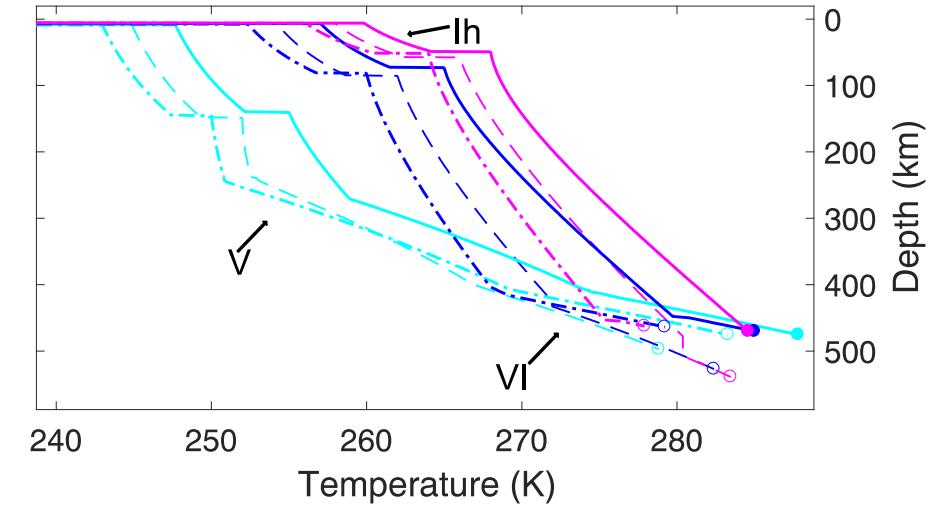
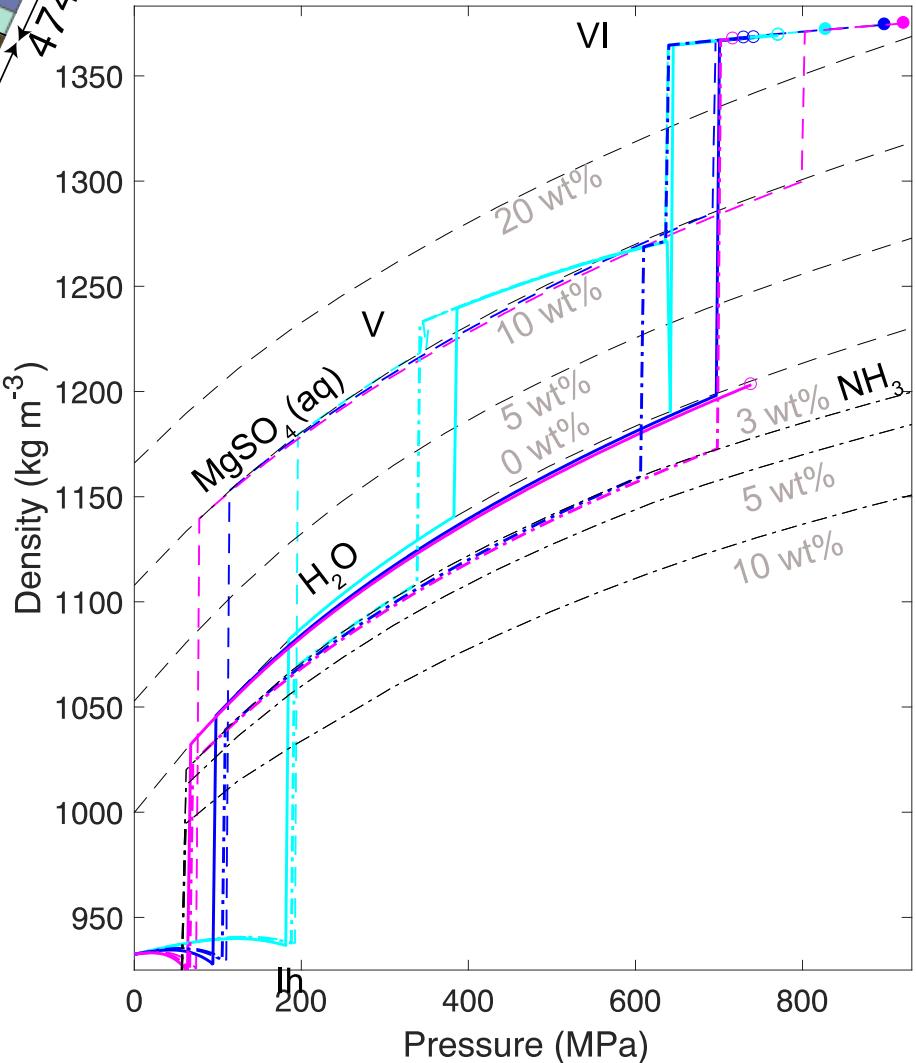
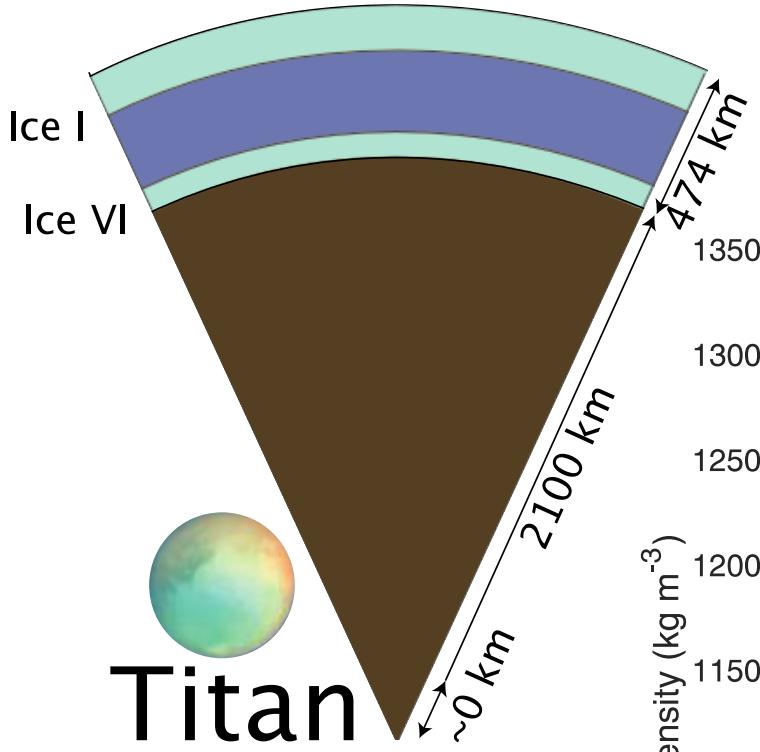




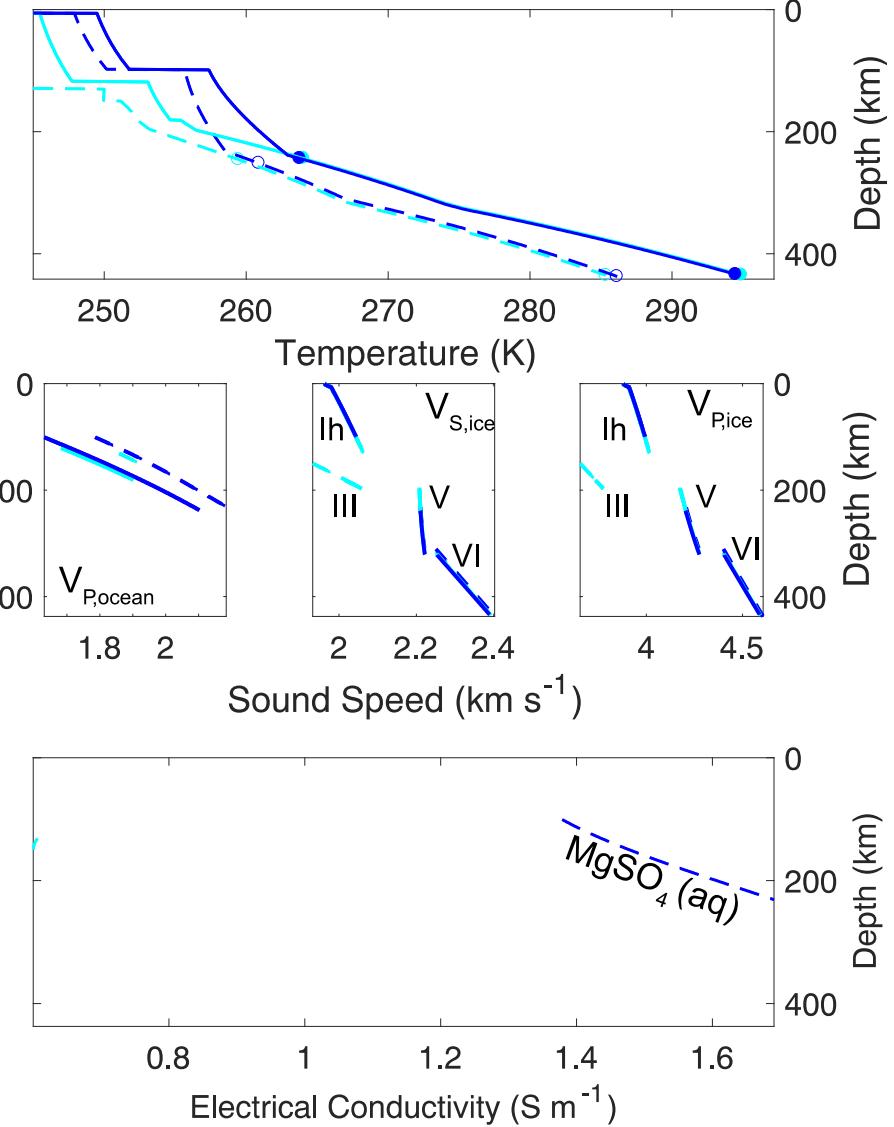
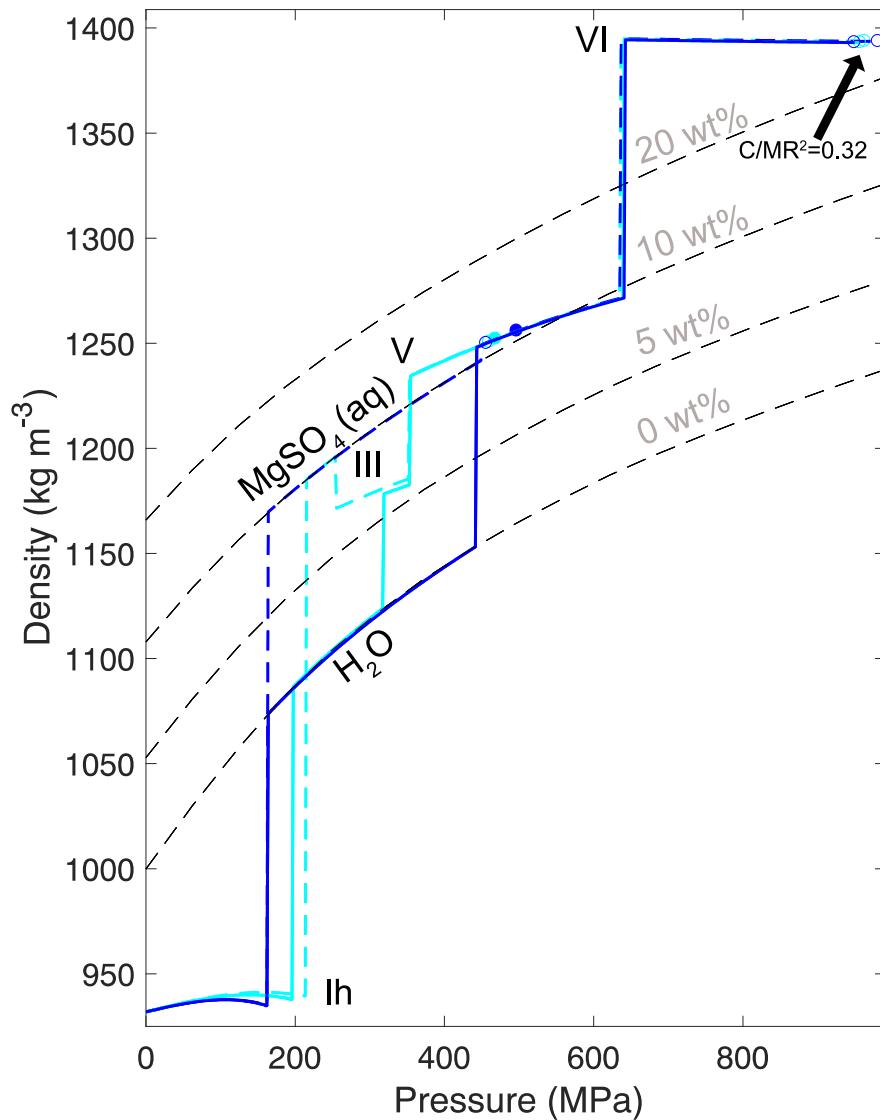
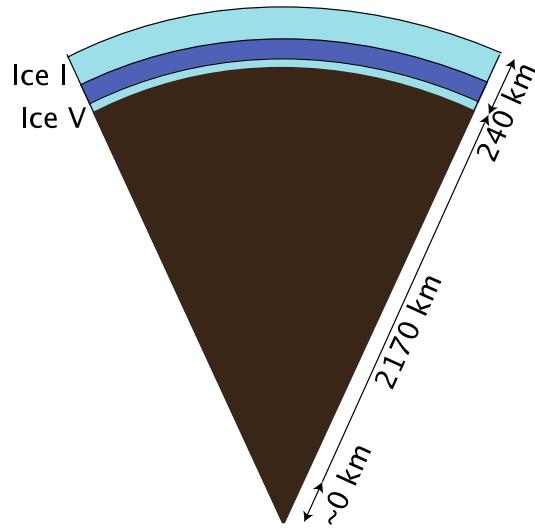
Geophysical Investigations of Habitability in Ice-Covered Ocean Worlds

Steven D. Vance¹ , Mark P. Panning¹ , Simon Stähler^{2,3} , Fabio Cammarano⁴ , Bruce G. Bills¹, Gabriel Tobie^{5,6} , Shunichi Kamata⁷ , Sharon Kedar¹, Christophe Sotin¹, William T. Pike⁸ , Ralph Lorenz⁹ , Hsin-Hua Huang^{10,11} , Jennifer M. Jackson¹⁰, and Bruce Banerdt¹



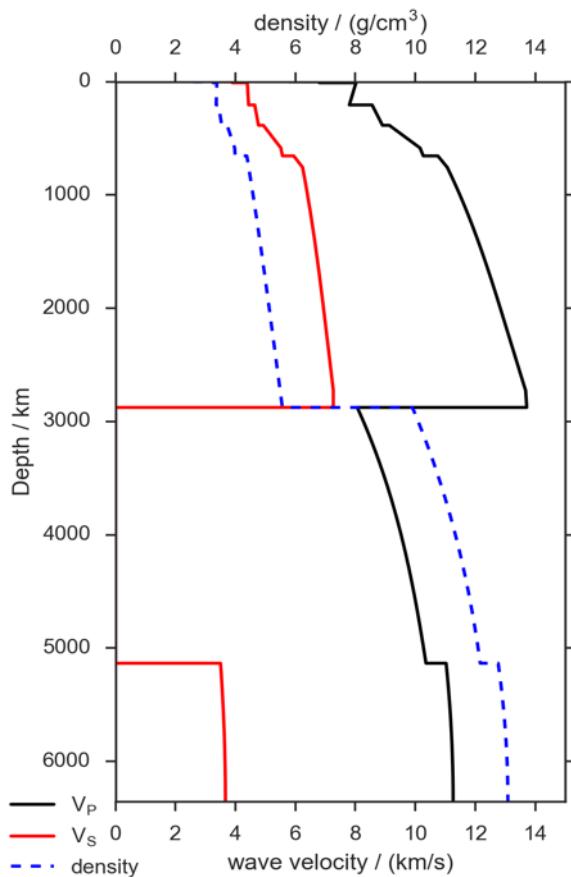


Callisto

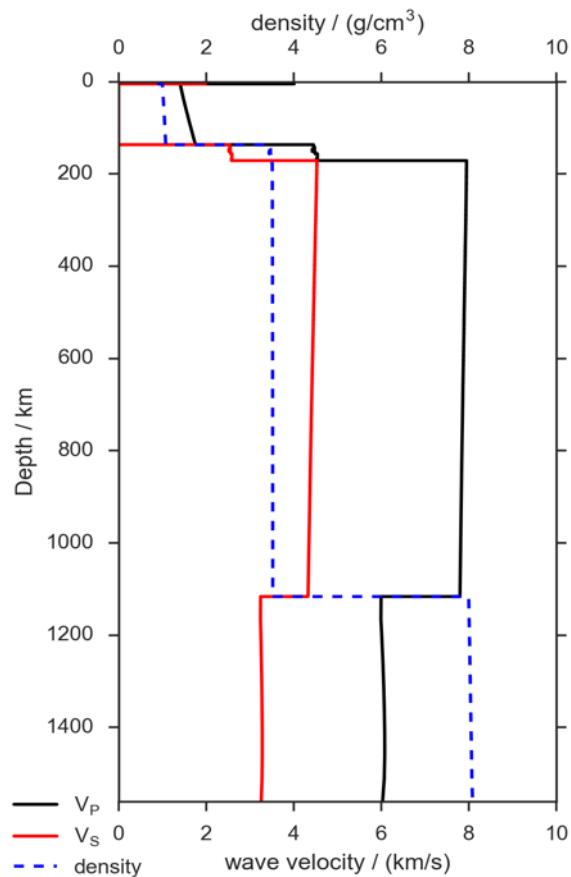


Seismic Models

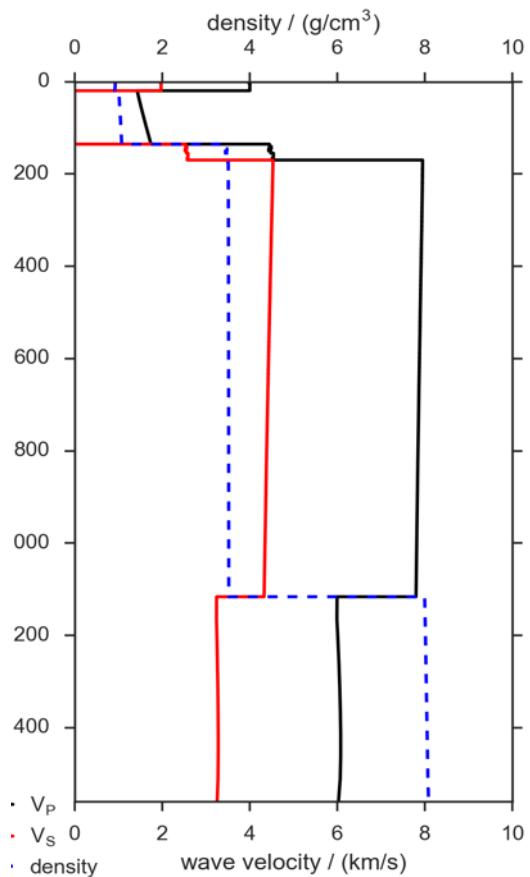
Earth



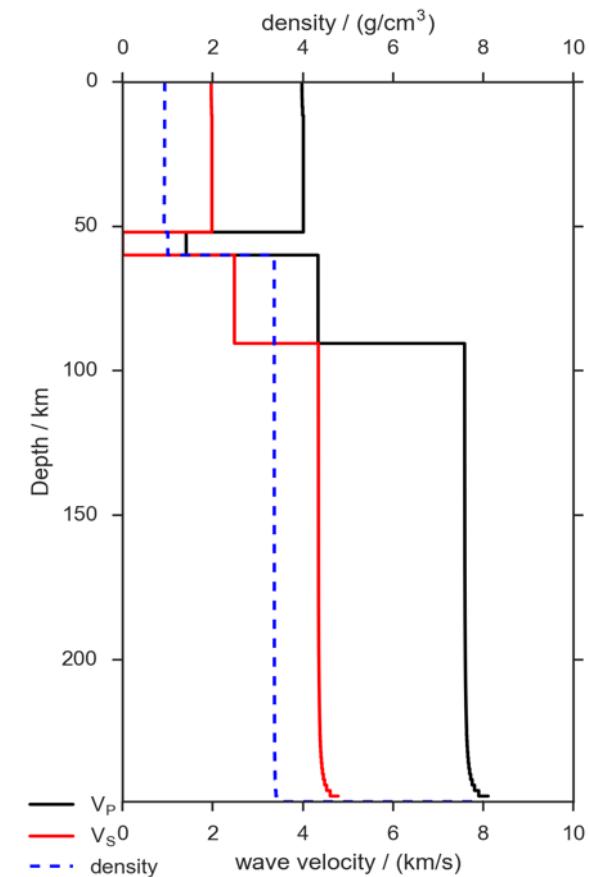
Europa (5km Ice)



Europa (20km Ice)

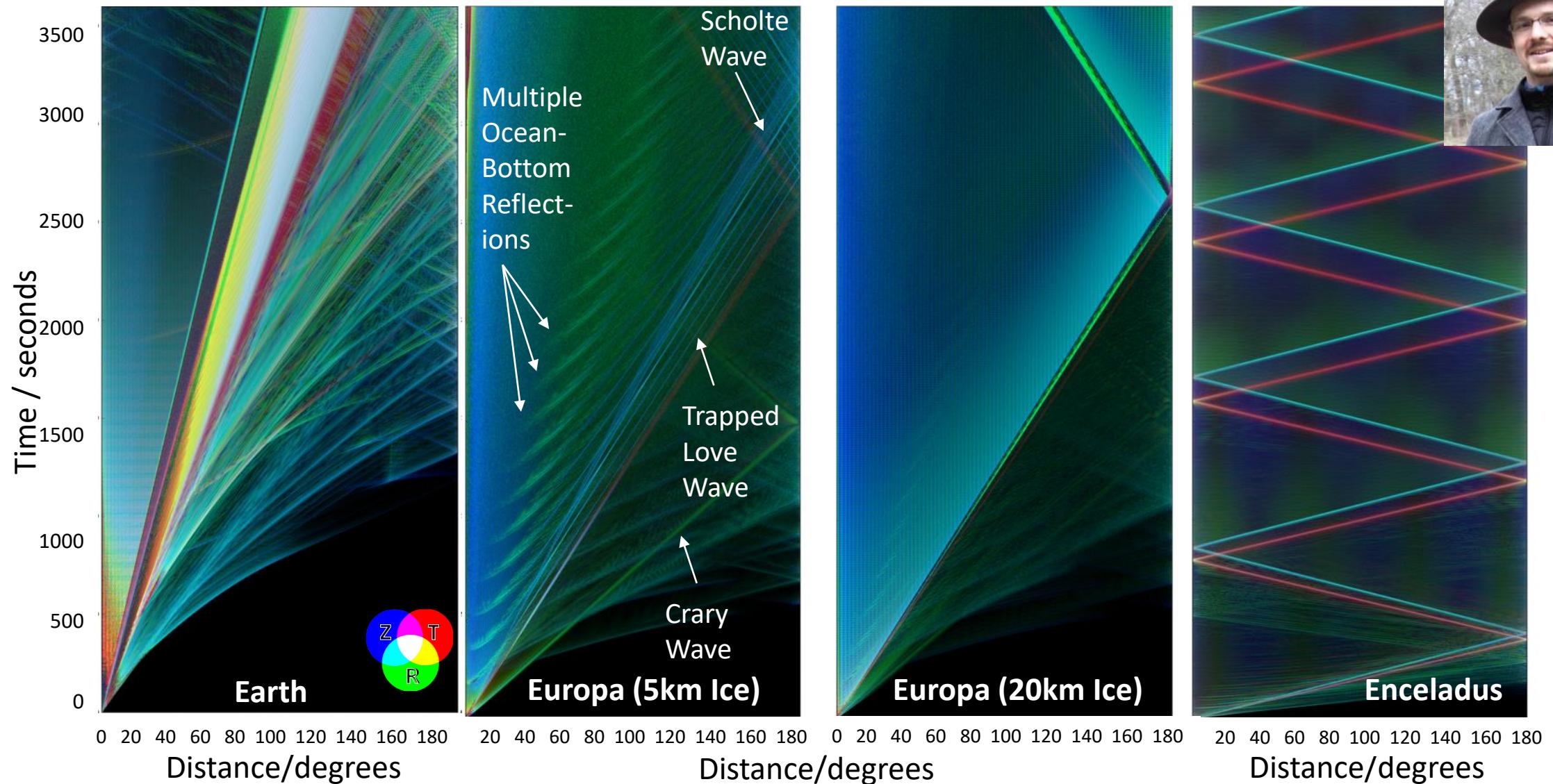


Enceladus



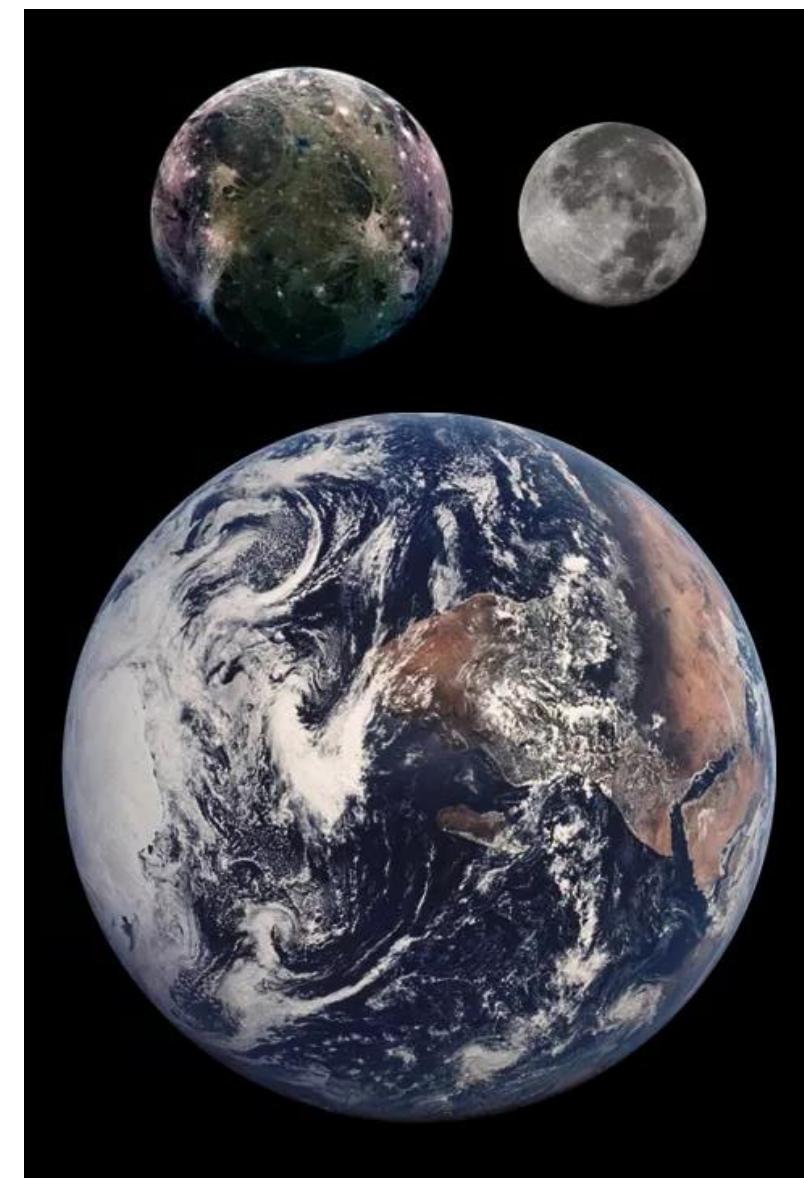
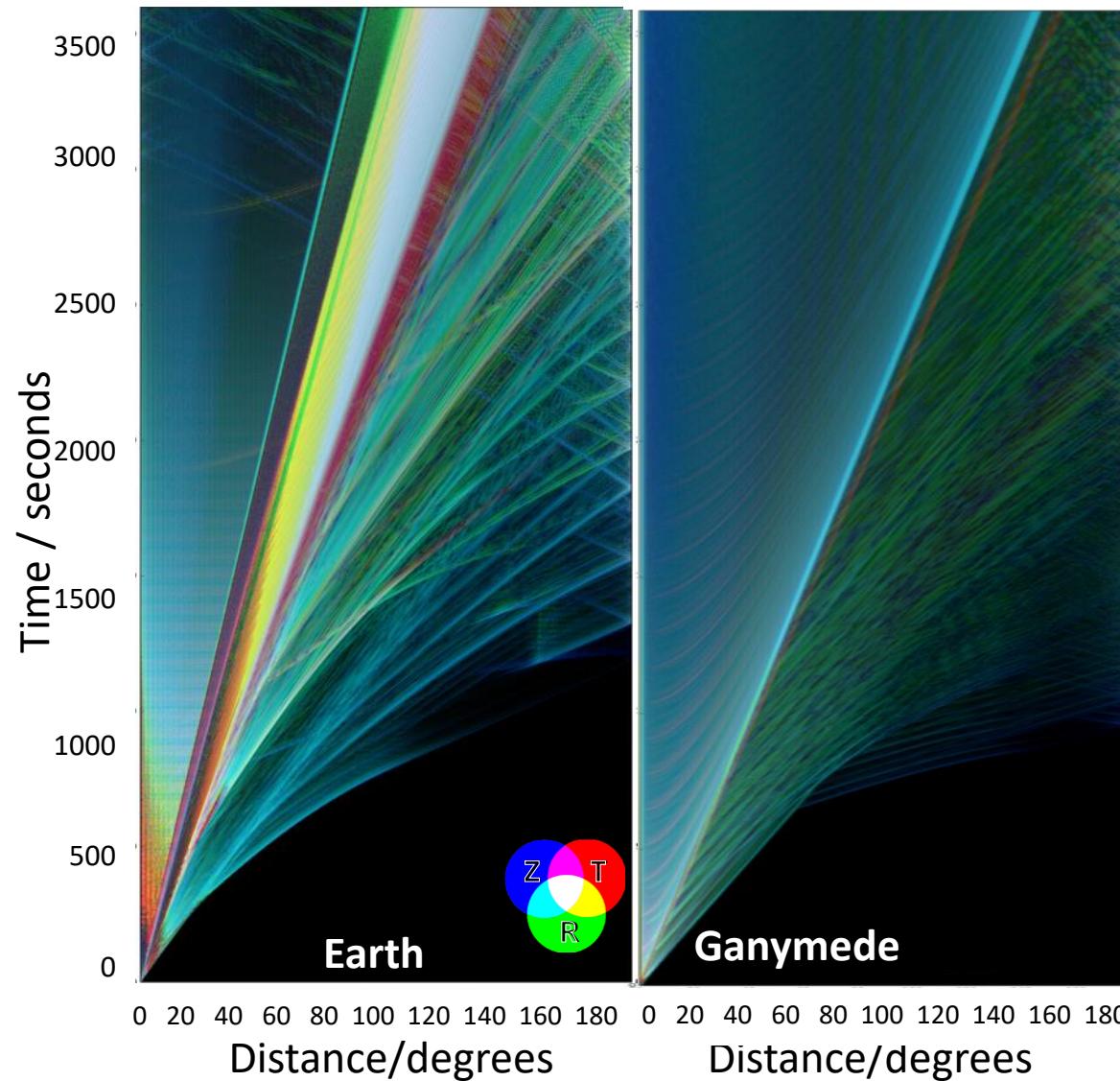
Each Ocean World Has a Unique Seismic Signature

Stähler et al. 2018, JGR.

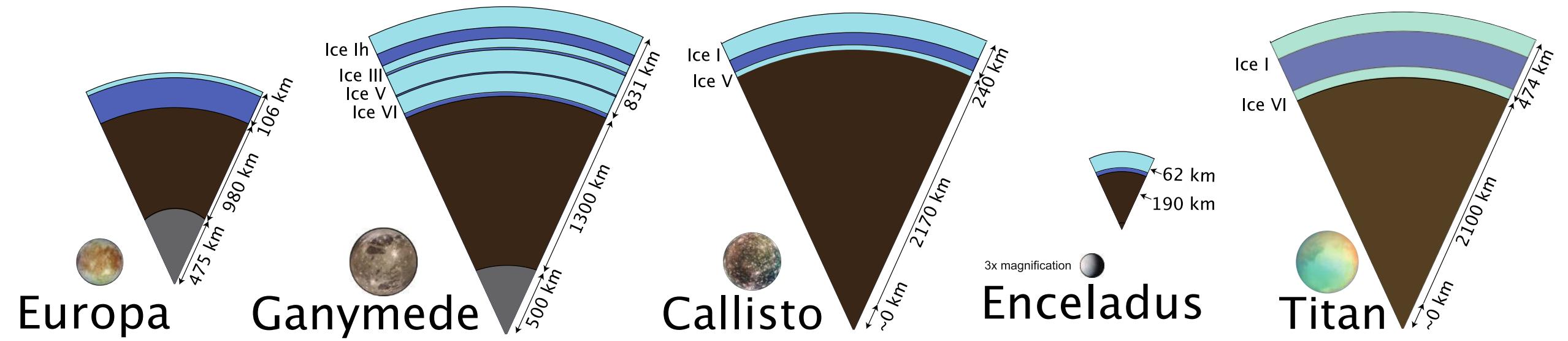


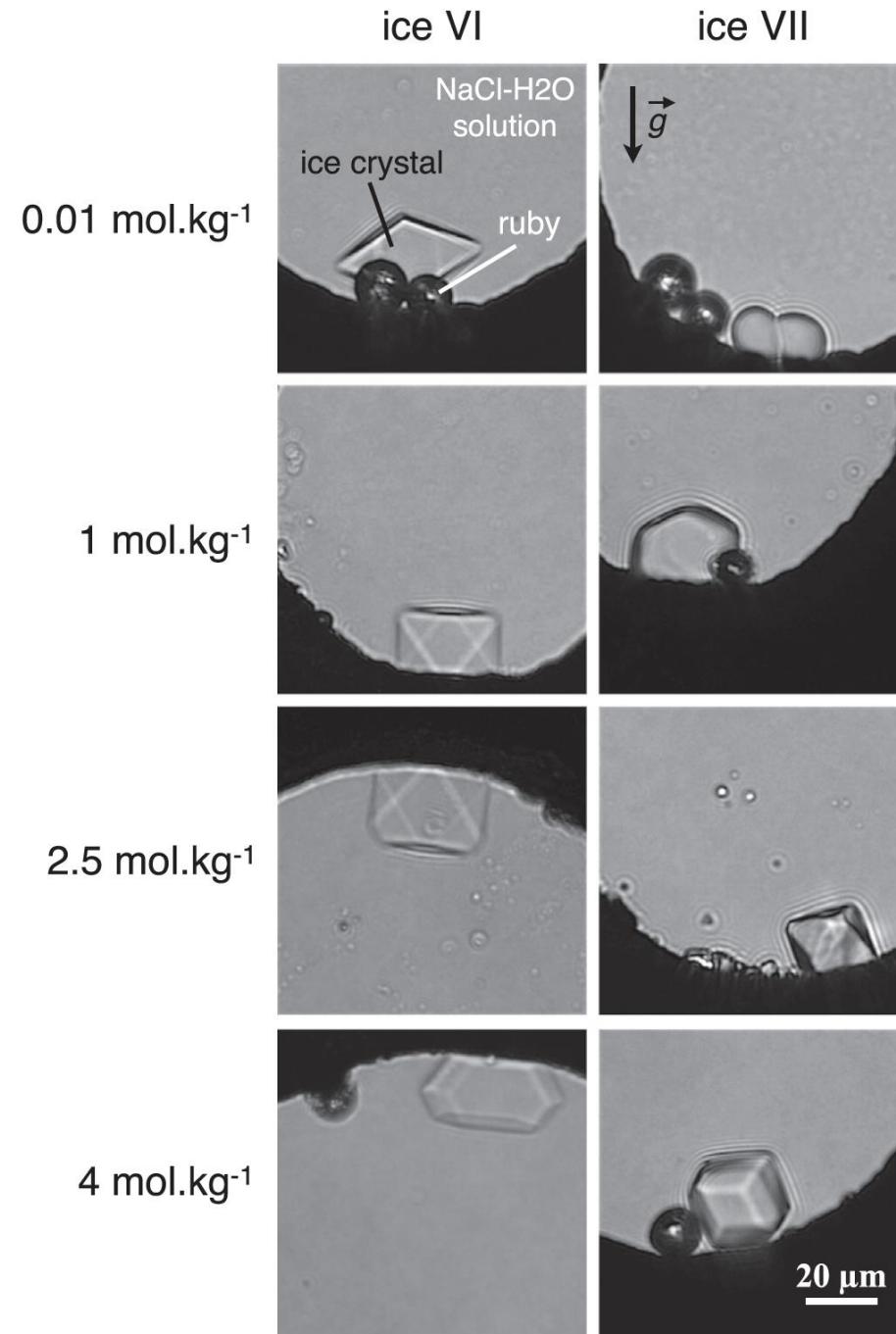
Each Ocean World Has a Unique Seismic Signature

Stähler et al. 2018, JGR.



Conclusions

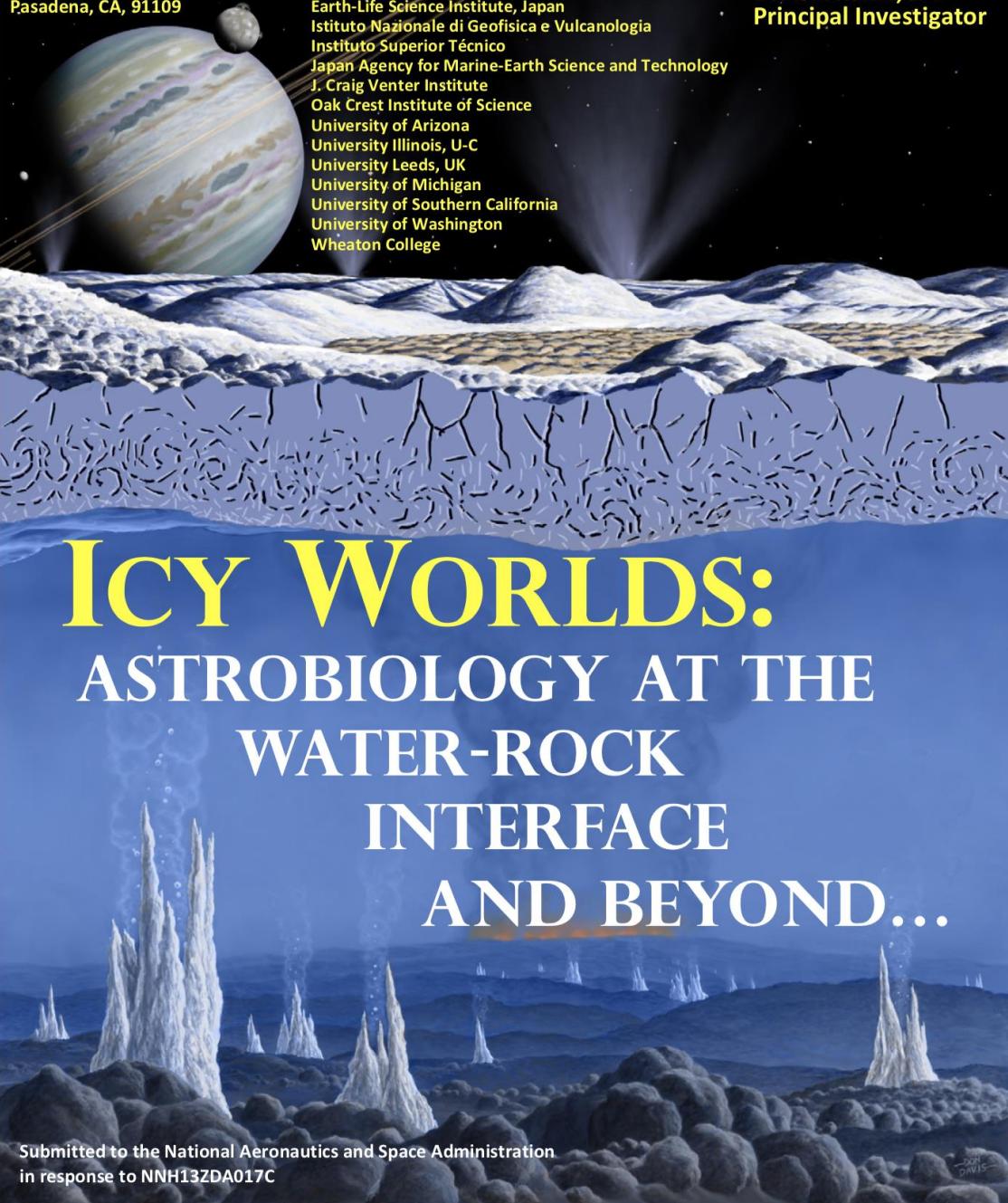




Journaux et al. 2013

Proposing Institution
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, CA, 91109

Participating Institutions
Arizona State University
California Institute of Technology
Desert Research Institute
Earth-Life Science Institute, Japan
Istituto Nazionale di Geofisica e Vulcanologia
Instituto Superior Técnico
Japan Agency for Marine-Earth Science and Technology
J. Craig Venter Institute
Oak Crest Institute of Science
University of Arizona
University Illinois, U-C
University Leeds, UK
University of Michigan
University of Southern California
University of Washington
Wheaton College



**Dr. Isik Kanik, JPL
Principal Investigator**

Submitted to the National Aeronautics and Space Administration
in response to NNH13ZDA017C

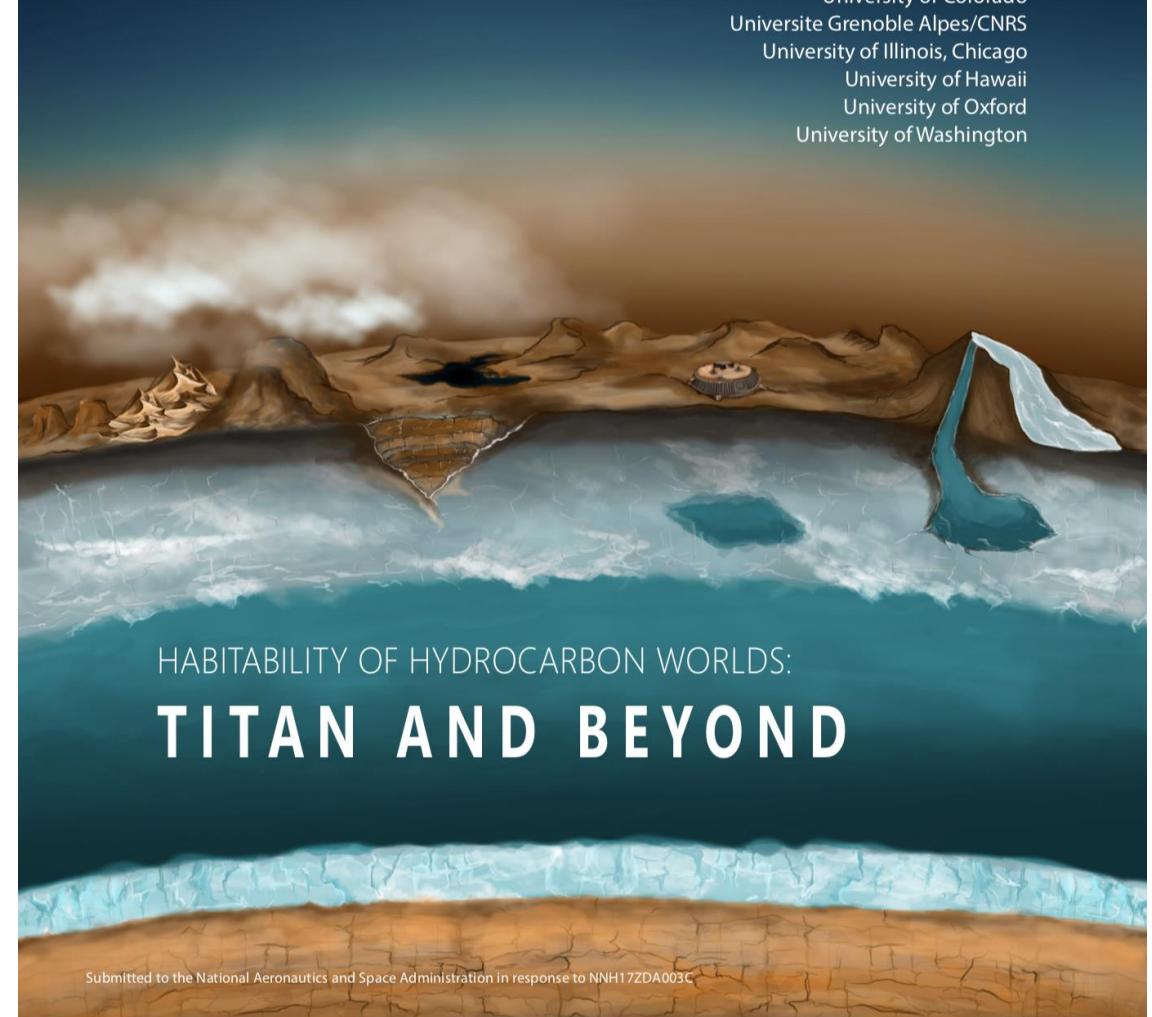
Proposing Institution

Jet Propulsion Laboratory
California Institute of
Technology
4800 Oak Grove Drive
Pasadena, CA 91107

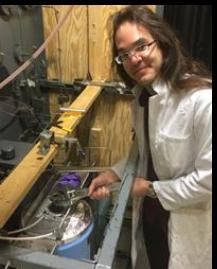
**Dr. Rosaly Lopes
Principal Investigator**

Participating Institutions

Aeolis Research
Cornell University
California Institute of Technology
Mt. San Antonio College
NASA Goddard Space Flight Center
Planetary Science Institute
Southwest Research Institute
University of Arizona
University of Bristol
University of California
University of Colorado
Université Grenoble Alpes/CNRS
University of Illinois, Chicago
University of Hawaii
University of Oxford
University of Washington



Submitted to the National Aeronautics and Space Administration in response to NNH17ZDA003C



Support:

- NASA Outer Planets Research, Solar System Workings, Habitable Worlds Programs
- NASA Astrobiology Institute Icy Worlds Initiative
- Tokyo Institute of Technology, Earth-Life Science Institute

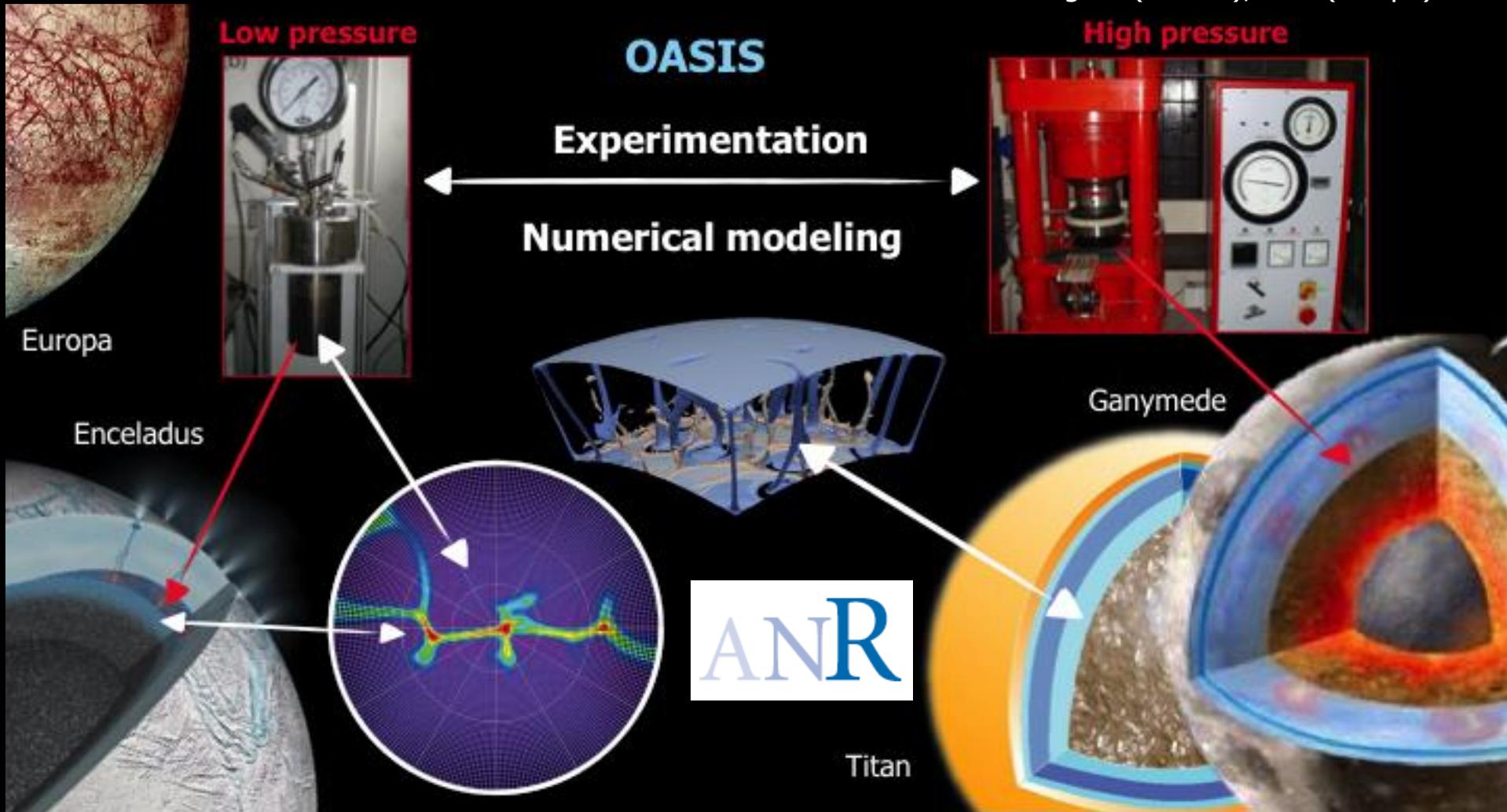


UNIVERSITÉ DE NANTES

Project OASIS: Organic and Aqueous Systems in Icy Satellites

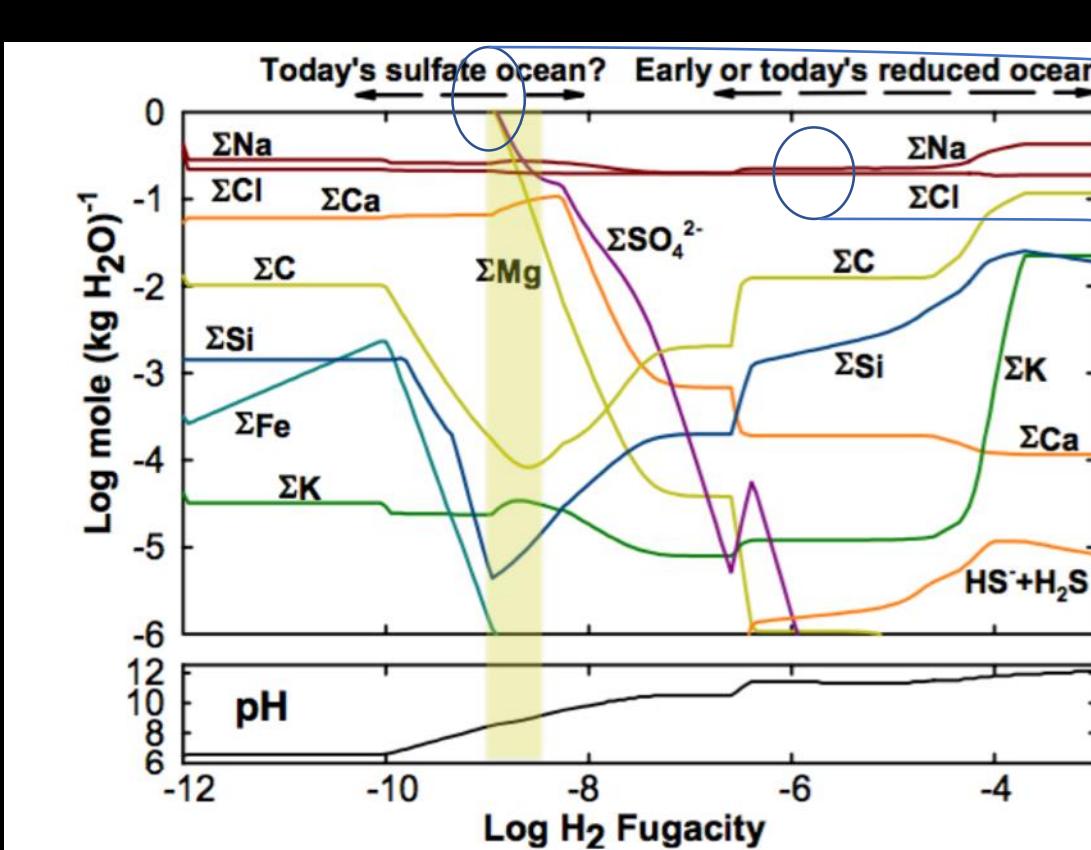
OASIS strategy: Combining experimental and modeling approaches to provide constraints on the aqueous alteration processes occurring inside icy worlds from their accretion to present.

OASIS consortium (P.I. G. Tobie)
France: LPG (Nantes), ISTerre (Grenoble), CRPG (Nancy); Czech Rep.: Charles Univ. (Prague); Germany: Univ. Heidelberg; US: JPL-Caltech (Pasadena), Univ. Washington (Seattle), ASU (Tempe)

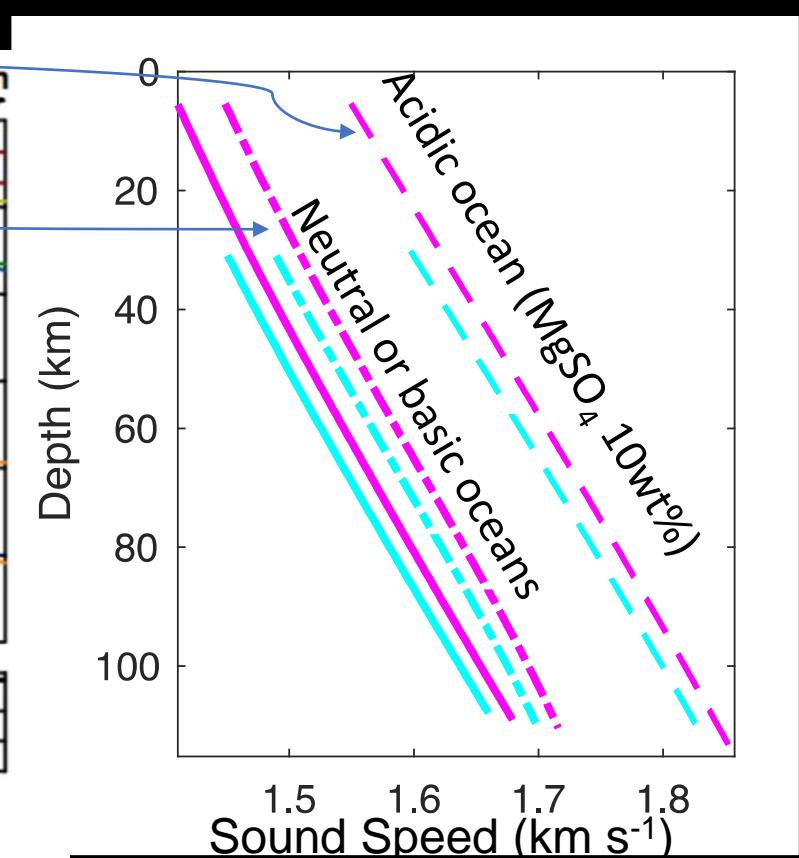




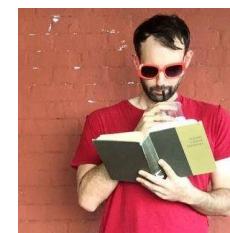
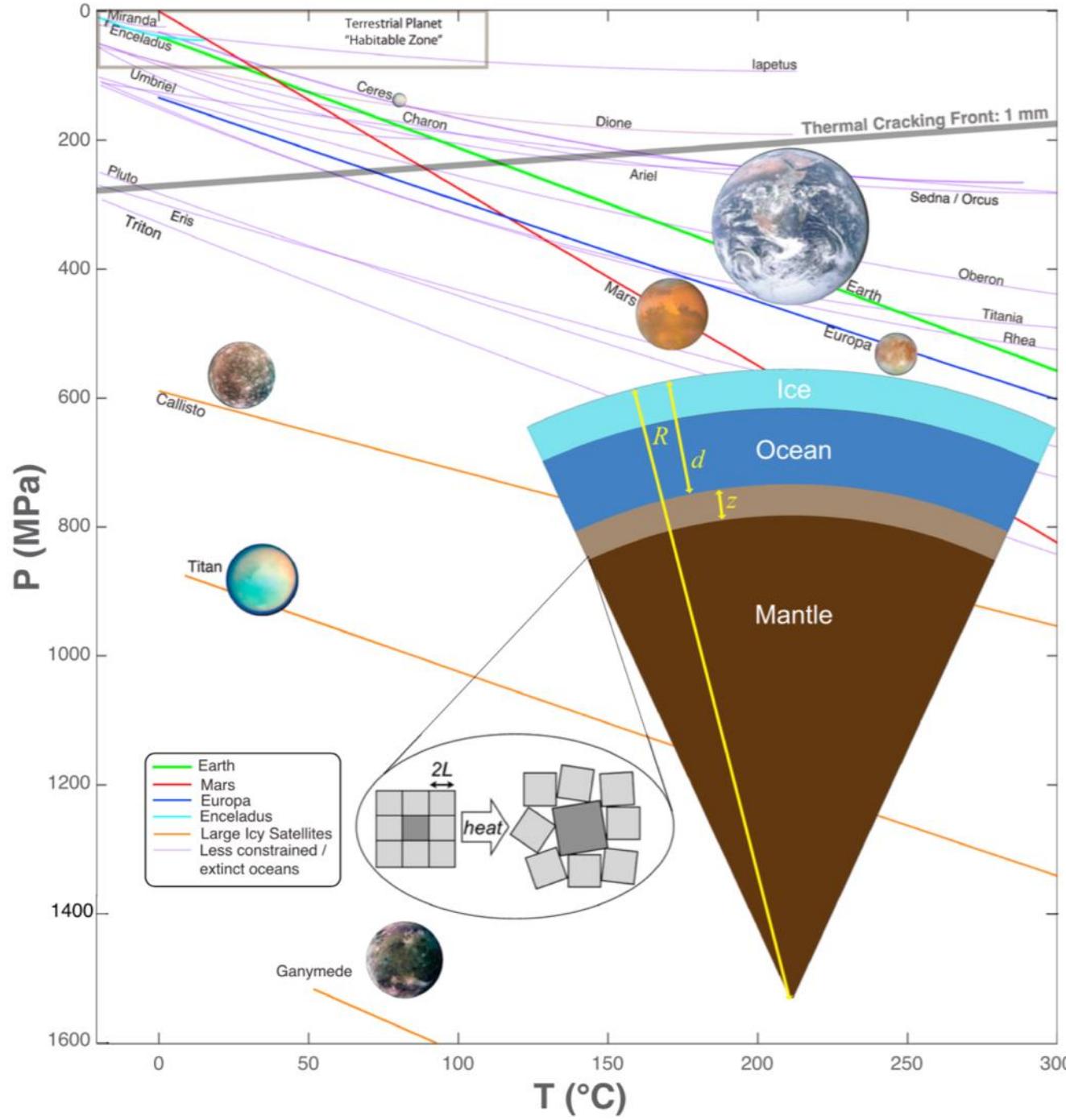
MgSO_4
 Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.



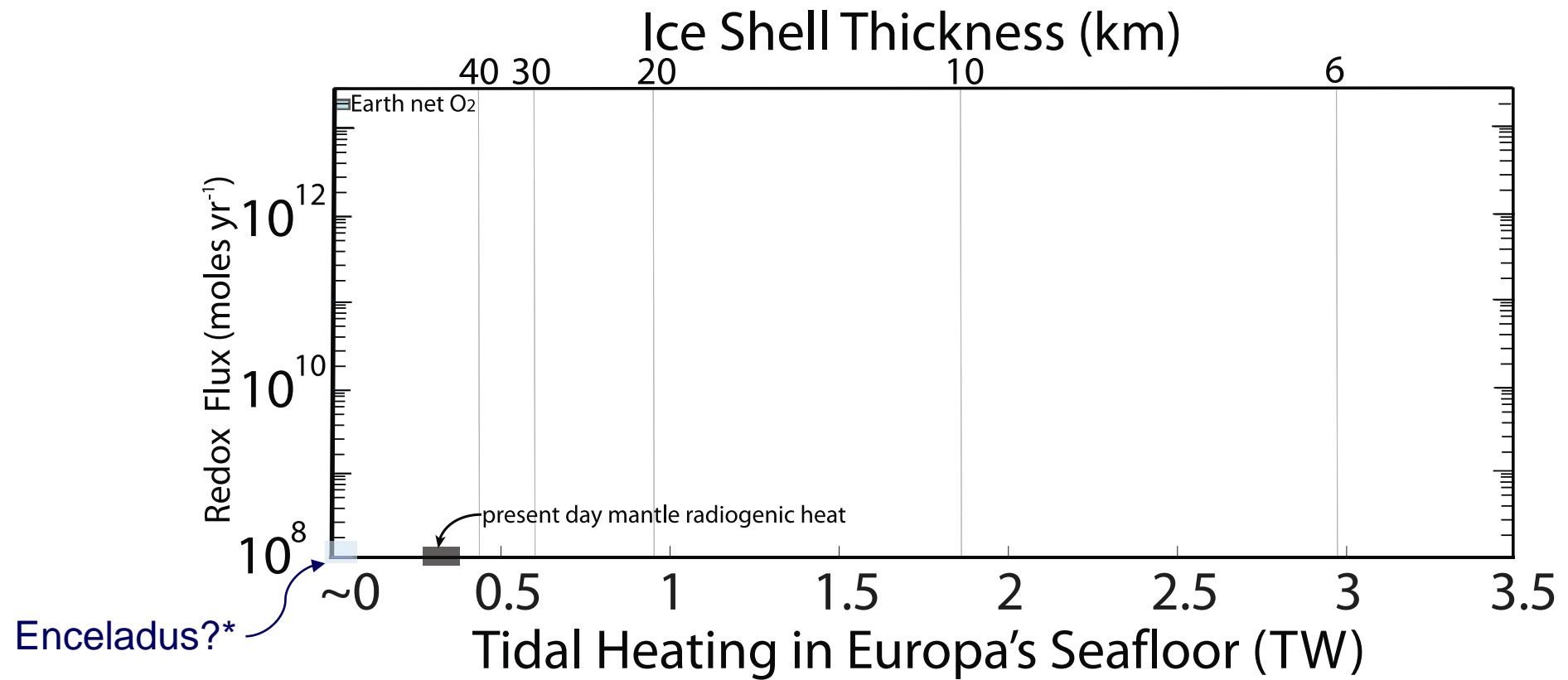
Modified from Zolotov 2008



Modified from Vance et al. 2018, JGR

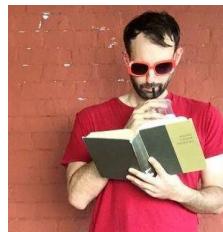


Vance, Hand, and Pappalardo 2016
Also Vance et al. 2007
→ “small ocean planets” (SOPs!)



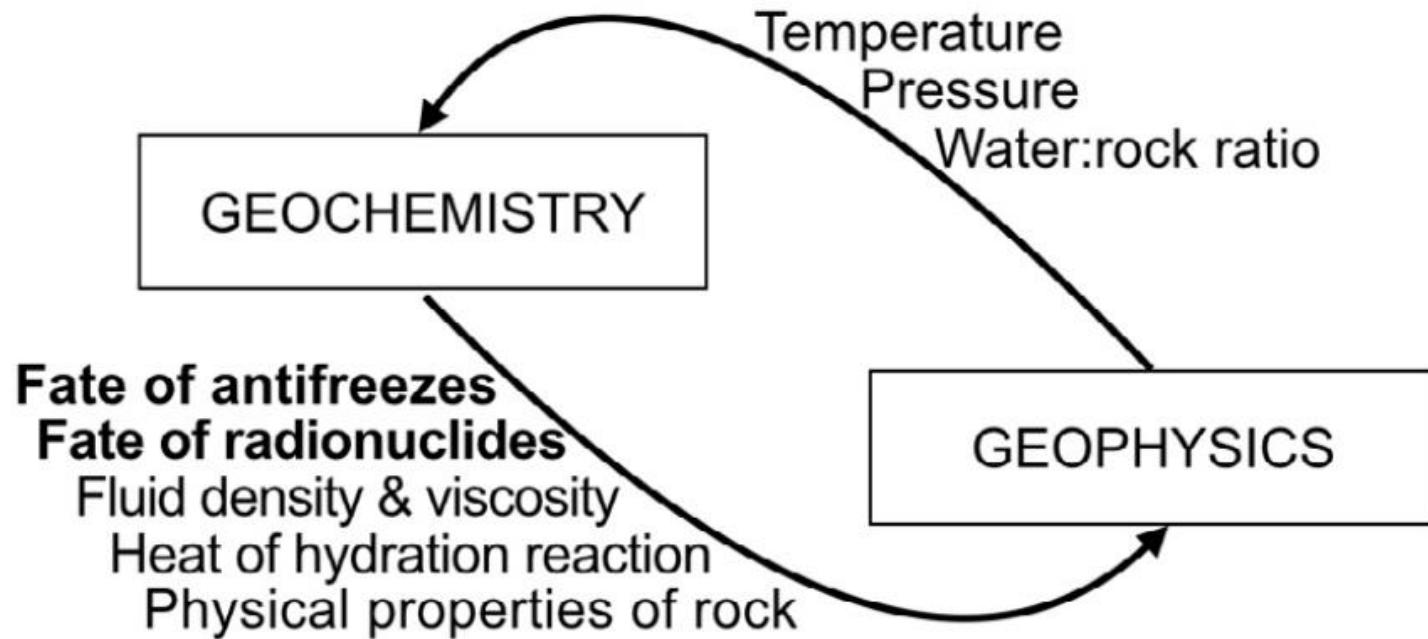
100km Europa ocean
vs
10km Enceladus ocean

$14 \text{ mmol mL}^{-1} \text{ yr}^{-1}$
vs
 $0.9 \text{ mmol mL}^{-1} \text{ yr}^{-1}$



*Ray et al., this meeting (abs. 6024; 10^{16} mol O_2 per $4.5 \times 10^9 \text{ yr}$)

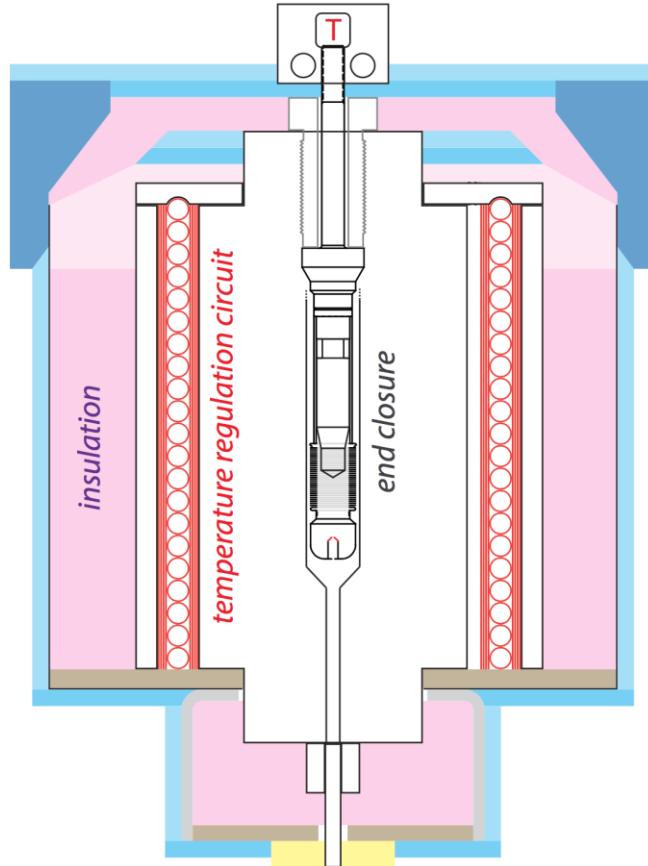
Vance, Hand, and Pappalardo, 2016



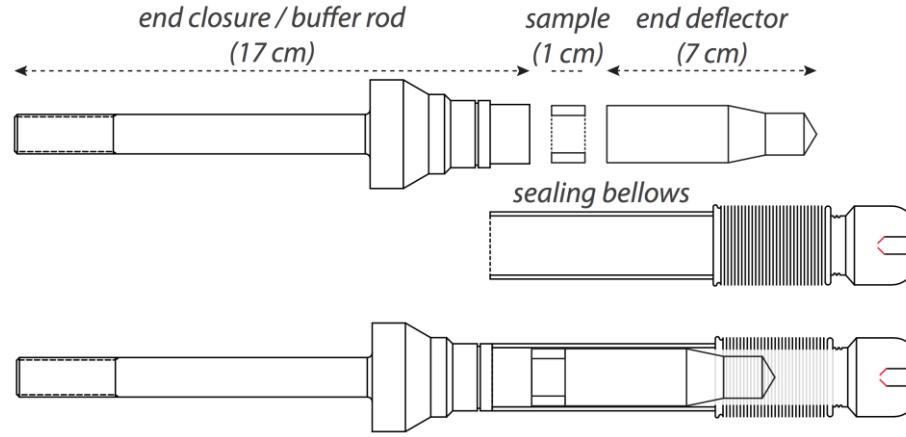
Neveu, Desch, and Castillo-Rogez 2017

Speed of sound: the Na-Mg-Cl-SO₄ brines

A high-pressure apparatus to measure sound speeds



Insulated high-pressure tank

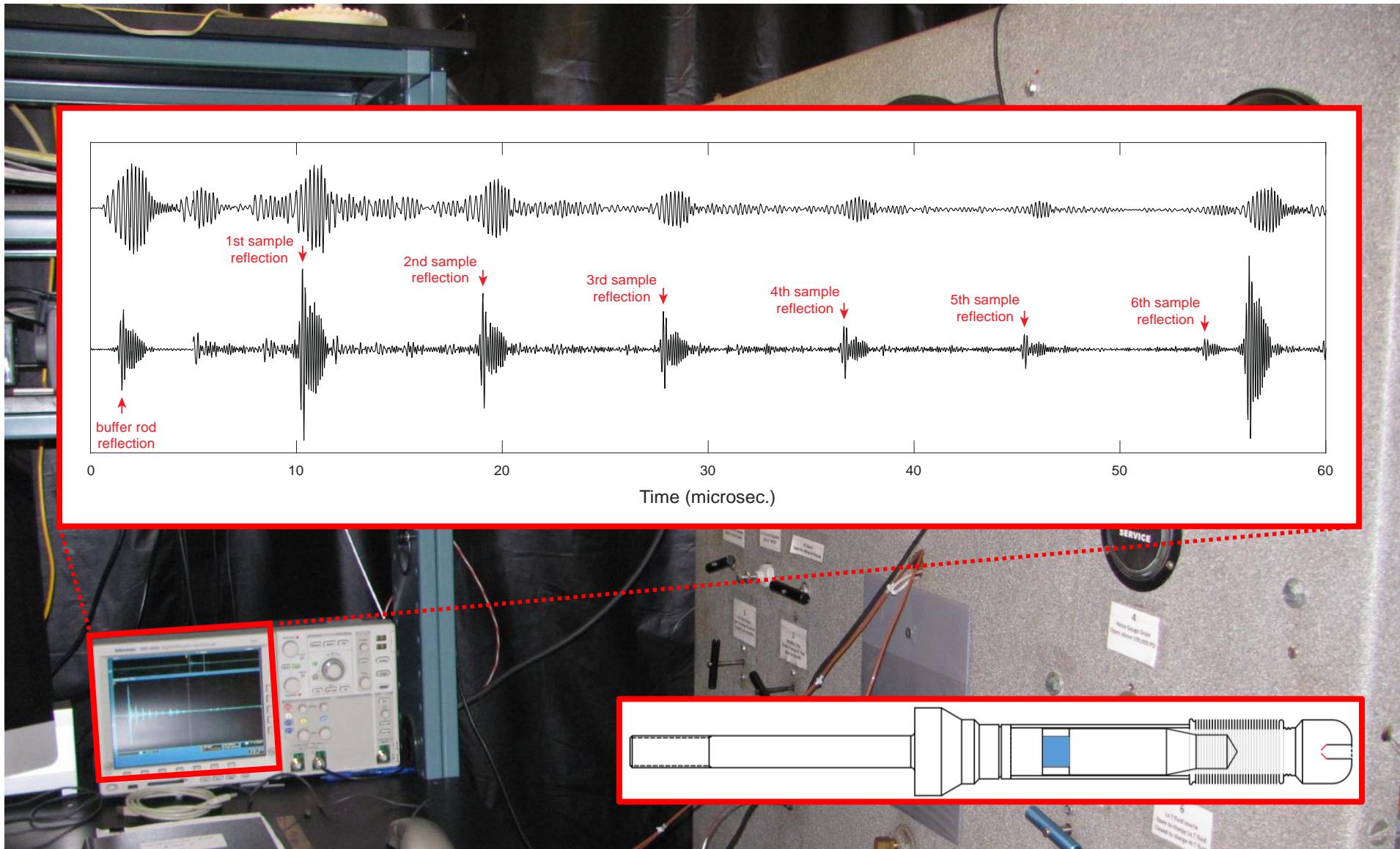


The end supports the sample chamber (inside the tank), and the ultrasonic transducer (outside the tank). The bellows adapt to change of sample volume (compressibility, expansivity) while keeping the sample pristine.

Maximum pressure: 800 MPa (Ti alloy).

Speed of sound: the Na-Mg-Cl-SO₄ brines

Sound speed measurements



Speed of sound: the Na-Mg-Cl-SO₄ brines

Sound speed, temperature and pressure measurements

SPEED OF SOUND (ultrasonic transducer)

- 3 – 6.5 MHz range (non dispersive frequency for water)
- 10 µs TWTT resolved at 1 ns: 0.01% accuracy

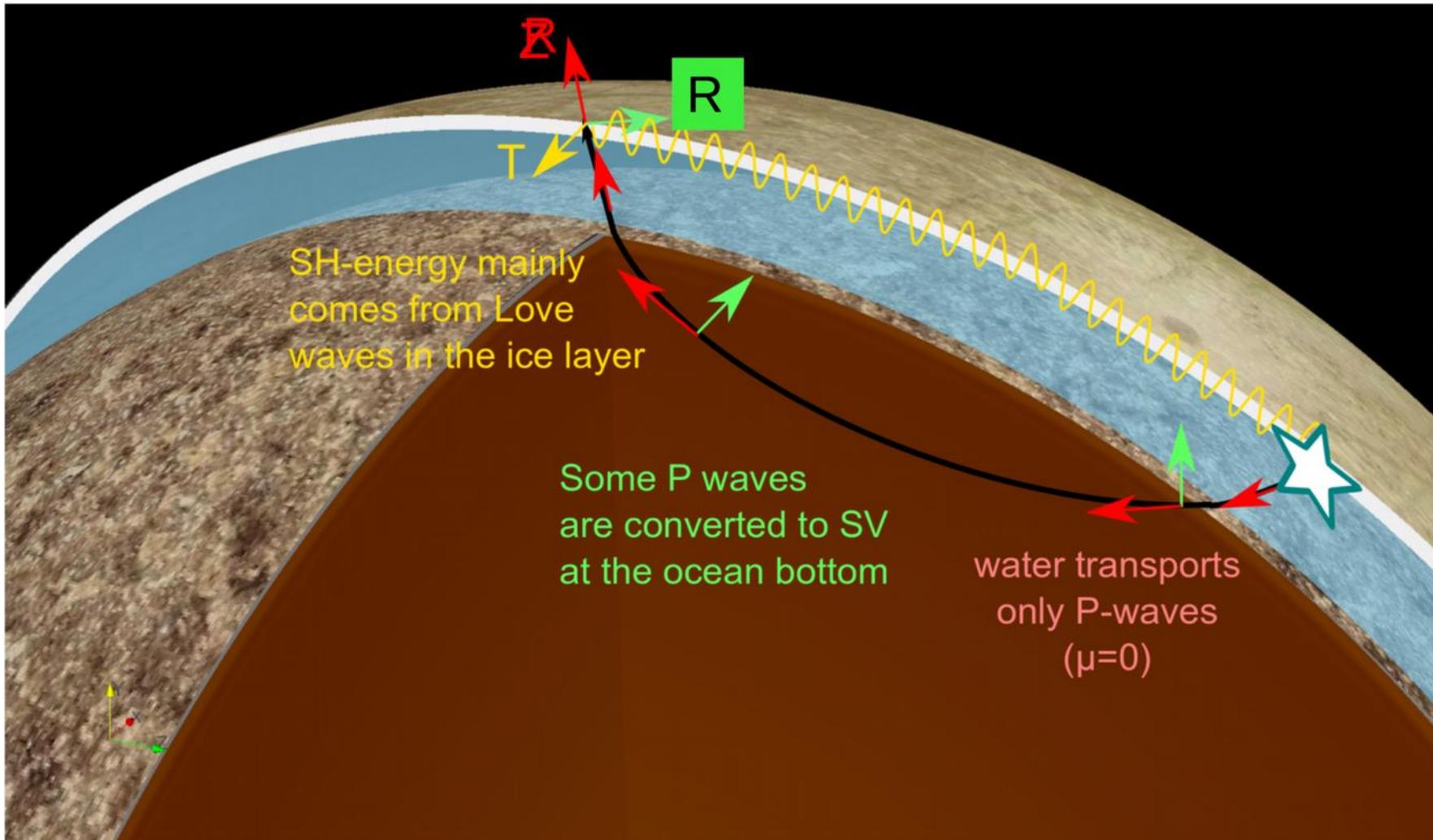
TEMPERATURE (T-type thermocouples & Pt-100 RTD)

- 0.02 K precision by T-type thermocouples
- 0.01 K accuracy given by Pt-100 RTD
- 0.1 K global accuracy for sample between 250-350 K

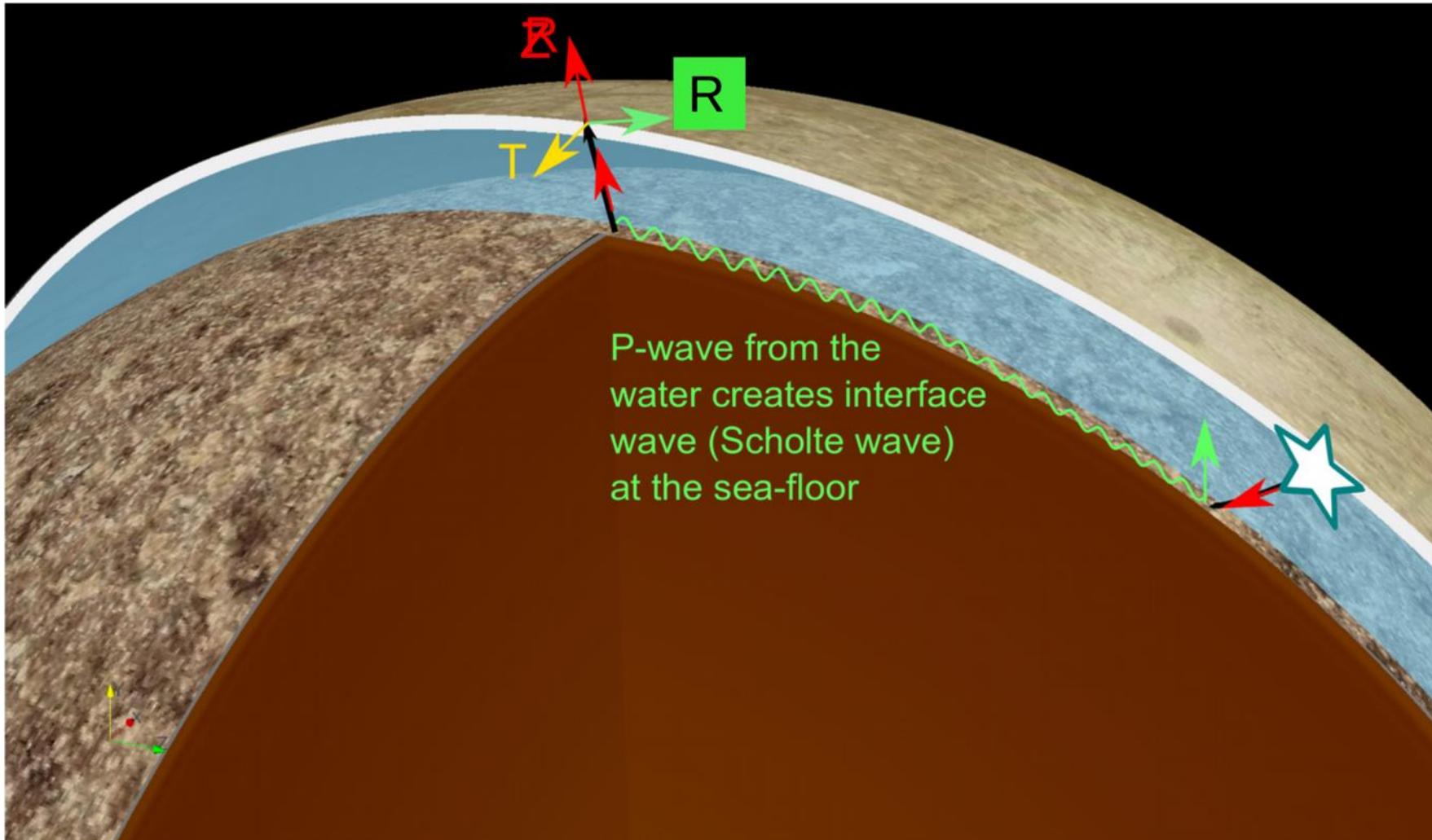
PRESSURE (pressure transducers)

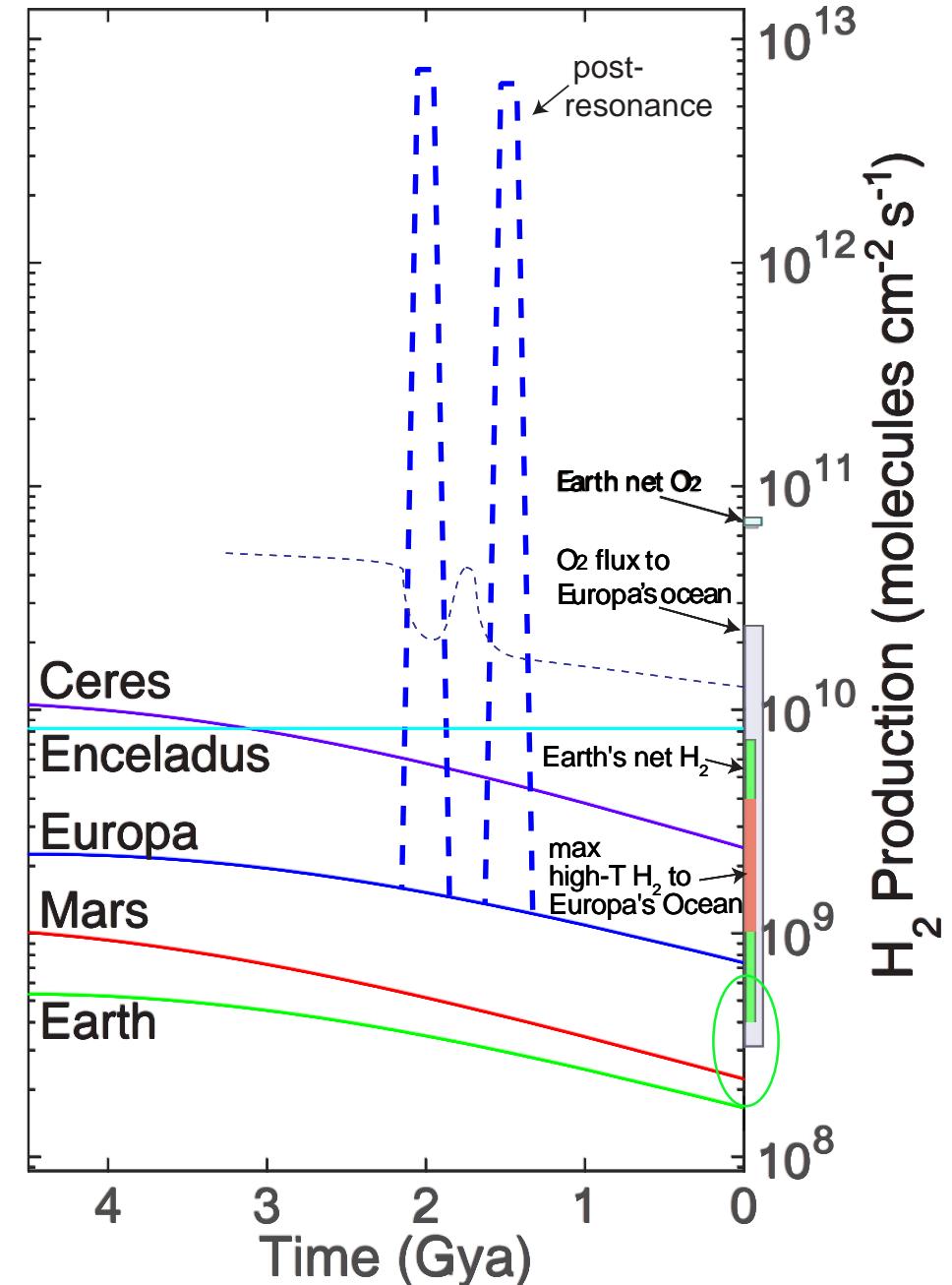
- 0.1 MPa precision on the 0.1-700 MPa range
- unresolved accuracy (NIST pressure standard?)

Sensing the mantle and ice



Sensing the mantle and ice





Vance, Hand, and Pappalardo, 2016

	Mean Radius in km	Bulk Density in kg m ⁻³	Moment of Inertia (C/MR ²)	Inferred H ₂ O thickness in km	Rotation Period In hrs	Radiogenic Heat in GW	Tidal Dissipation in GW	Seismic Energy Release in GW (%)
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Mars^c	3397	3933	0.3662 ±0.0017	n/a	24.6230	3,300	--	?
Europa^{d,e,f}	1565.0 ±8.0	2989 ±46	0.346 ±0.005	80-170	84.4	200	<10,000 >1000 (ocean) 1-10 (rock)	?
Ganymede^{e,f,g}	2631.17 ±1.7	1942.0 ±4.8	0.3115 ±0.0028	750-900	171.7	500	<50 >1 (ocean)	?
Callisto^{e,f}	2410.3 ±1.5	1834.4 ±3.4	0.3549 ±0.0042	350-450	400.5	400	<20 >4 (ocean)	?
Titan^{e,h,i}	2574.73 ±0.09	1879.8 ±0.2	0.3438 ±0.0005	500-700	382.7	400	<400 >11 (ocean)	?
Enceladus^{e,h,j}	252.1 ±0.1	1609 ±5	0.335	60-80	32.9	0.3	<20 >10 (ocean)	?

a) Williams et al., 2001 b) Goins et al., 1981; Williams et al., 1996; Siegler and Smekrar, 2014 c) Folkner et al., 1997, Nimmo and Faul, 2013 d) Tobie et al. 2003, Hussmann et al., 2006; Vance et al., 2007 e) Chen et al., 2014; Tyler, 2014 f) Schubert et al. 2004 g) Bland et al., 2015 h)

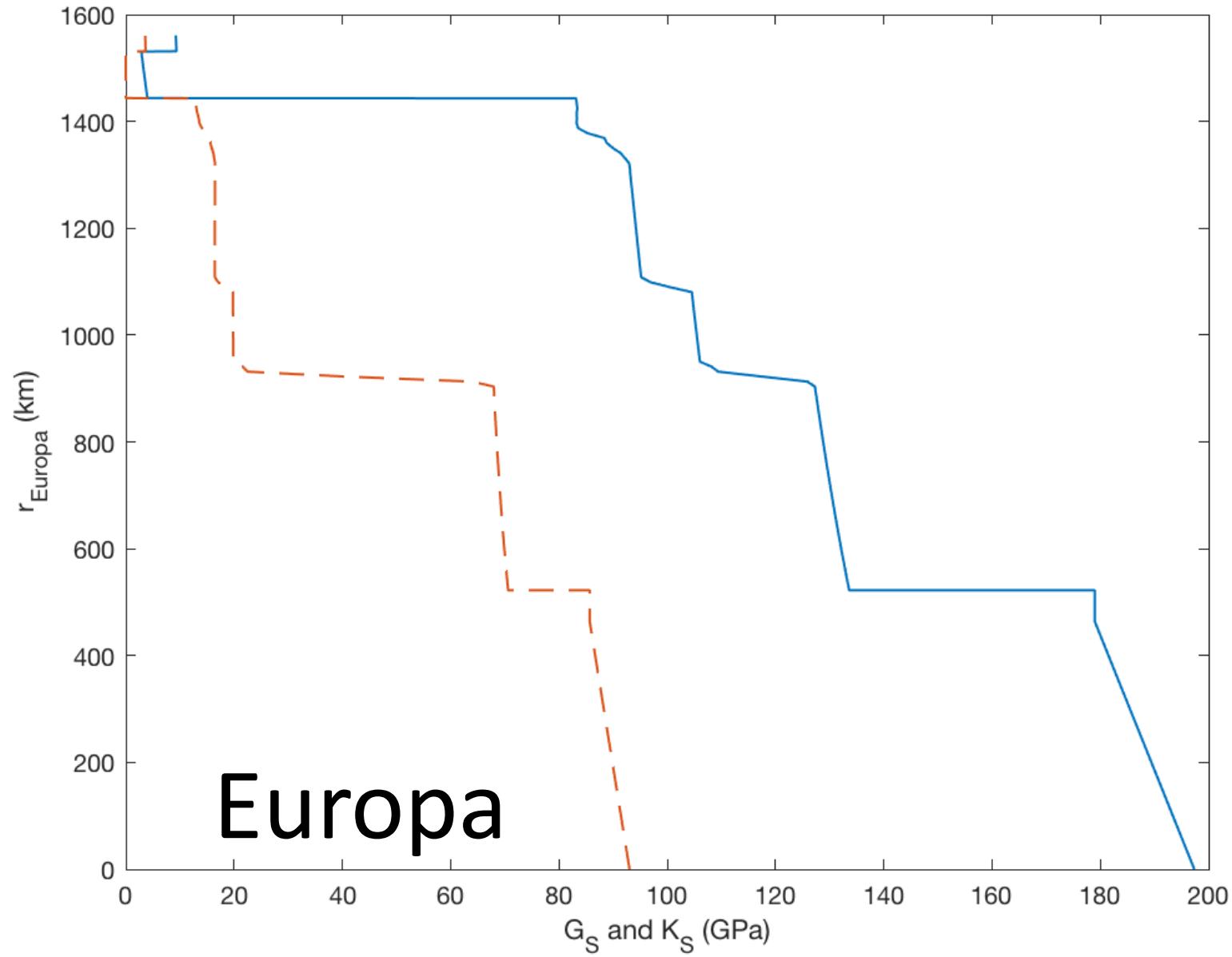
Tidal Dissipation

$$\tilde{\sigma}_{ij} = 2\tilde{\mu}(\omega)\tilde{\varepsilon}_{ij} + \left[K_E - \frac{2}{3}\tilde{\mu}(\omega) \right] \tilde{\varepsilon}_{kk} \delta_{ij},$$

where

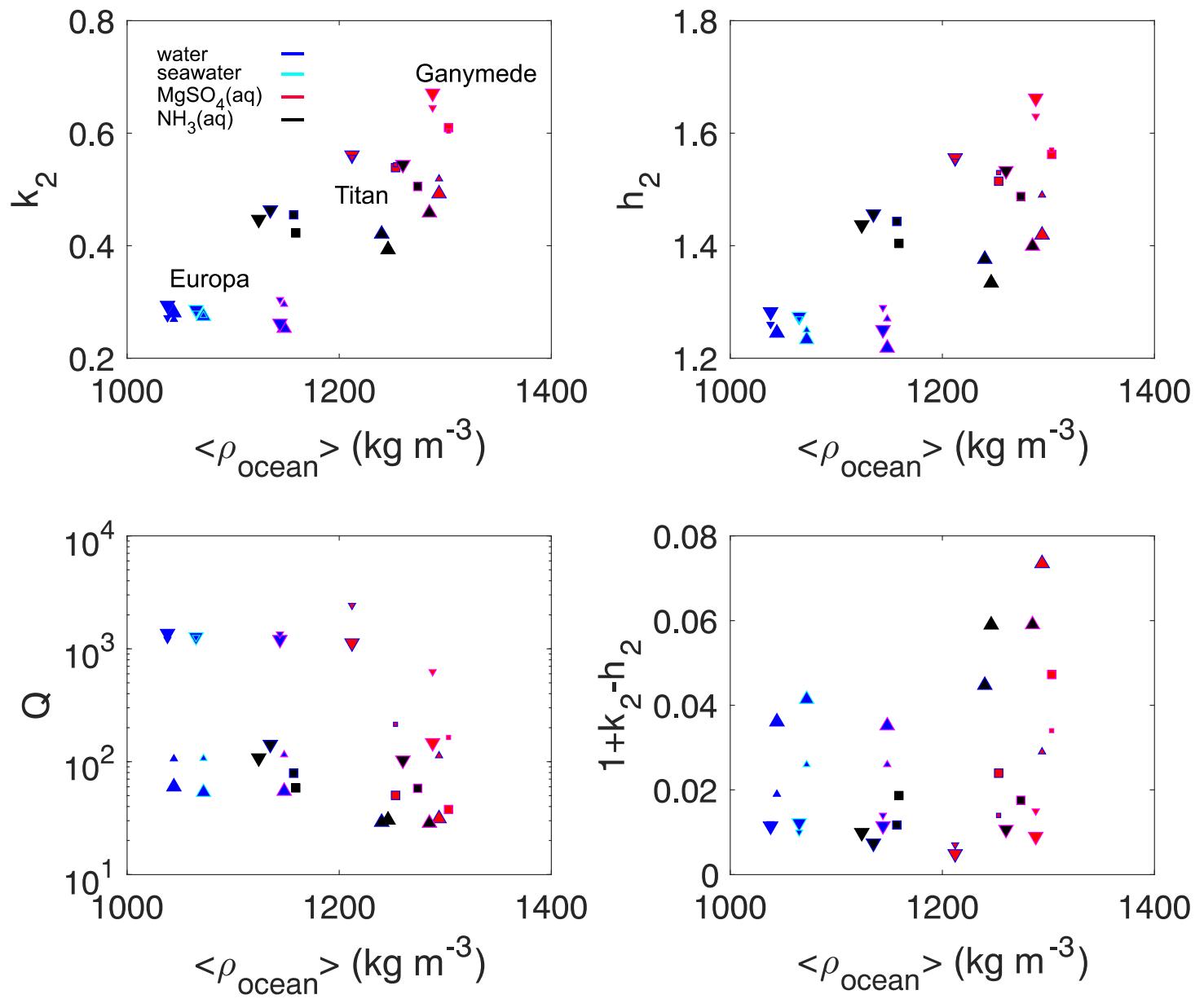
$$\tilde{\mu}(\omega) = \frac{\mu_E \omega^2 \eta^2}{\mu_E^2 + \omega^2 \eta^2} + i \frac{\mu_E^2 \omega \eta}{\mu_E^2 + \omega^2 \eta^2},$$

Tobie et al. 2006



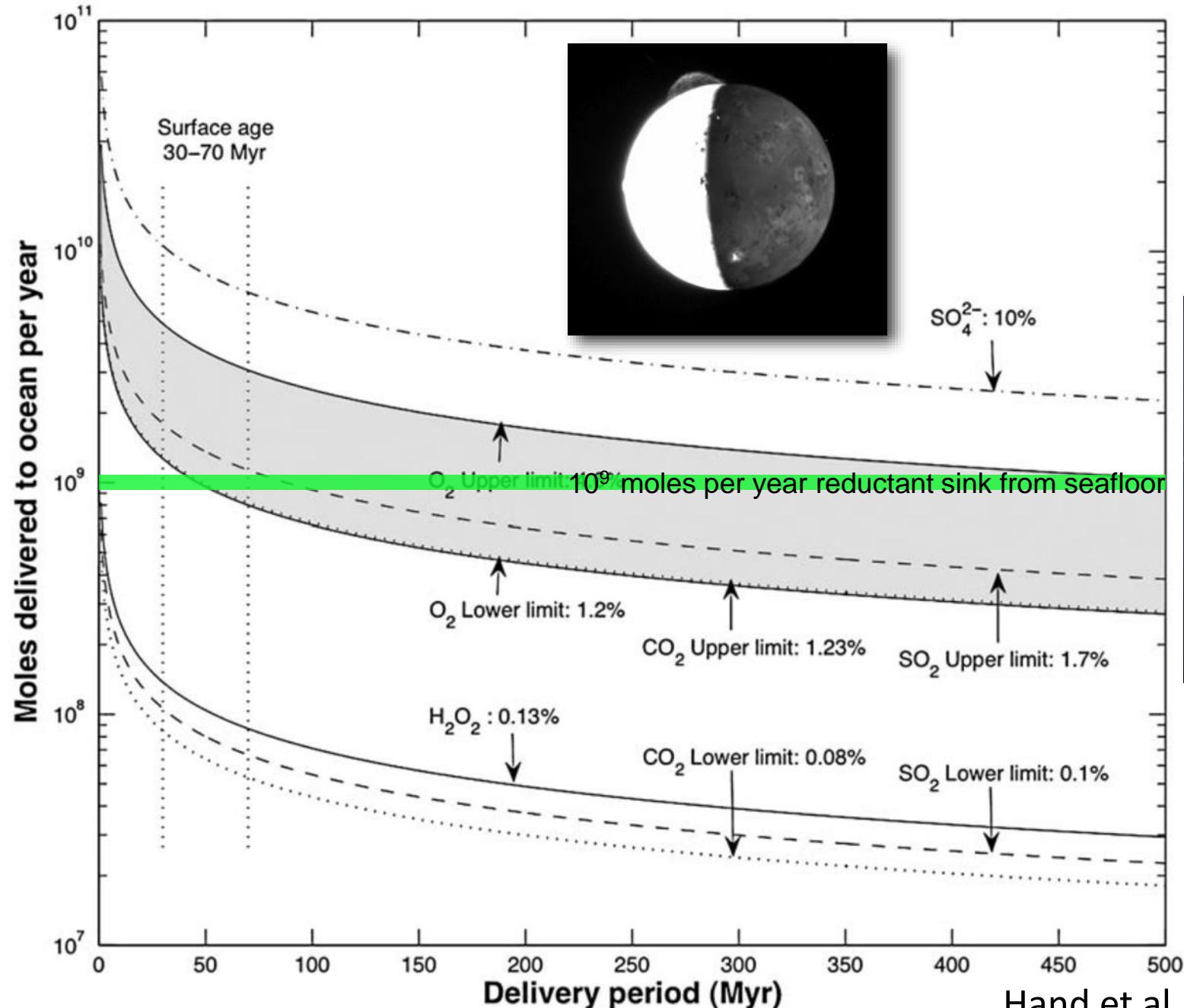
Vance et al. 2017 JGR

Tidal Dissipation



Contributed by
Gabriel Tobie and
Shunichi Kamata

Vance et al. 2017 JGR



Hand et al. 2007, 2009

High-T Hydrothermal Reductants

	Abundance(1) (mm)	Flux at Europa(2) ($\times 10^9$ moles yr^{-1})
CH_4	4.9	0.15
H_2	12.0	3.6
H_2S	33.0	1.0
Fe^{2+*}	0.30	0.09

1) McCollom 1999

2) McCollom (1999), scaled from Earth's 3×10^{13} kg yr^{-1} (Elderfield and Schultz 1996)

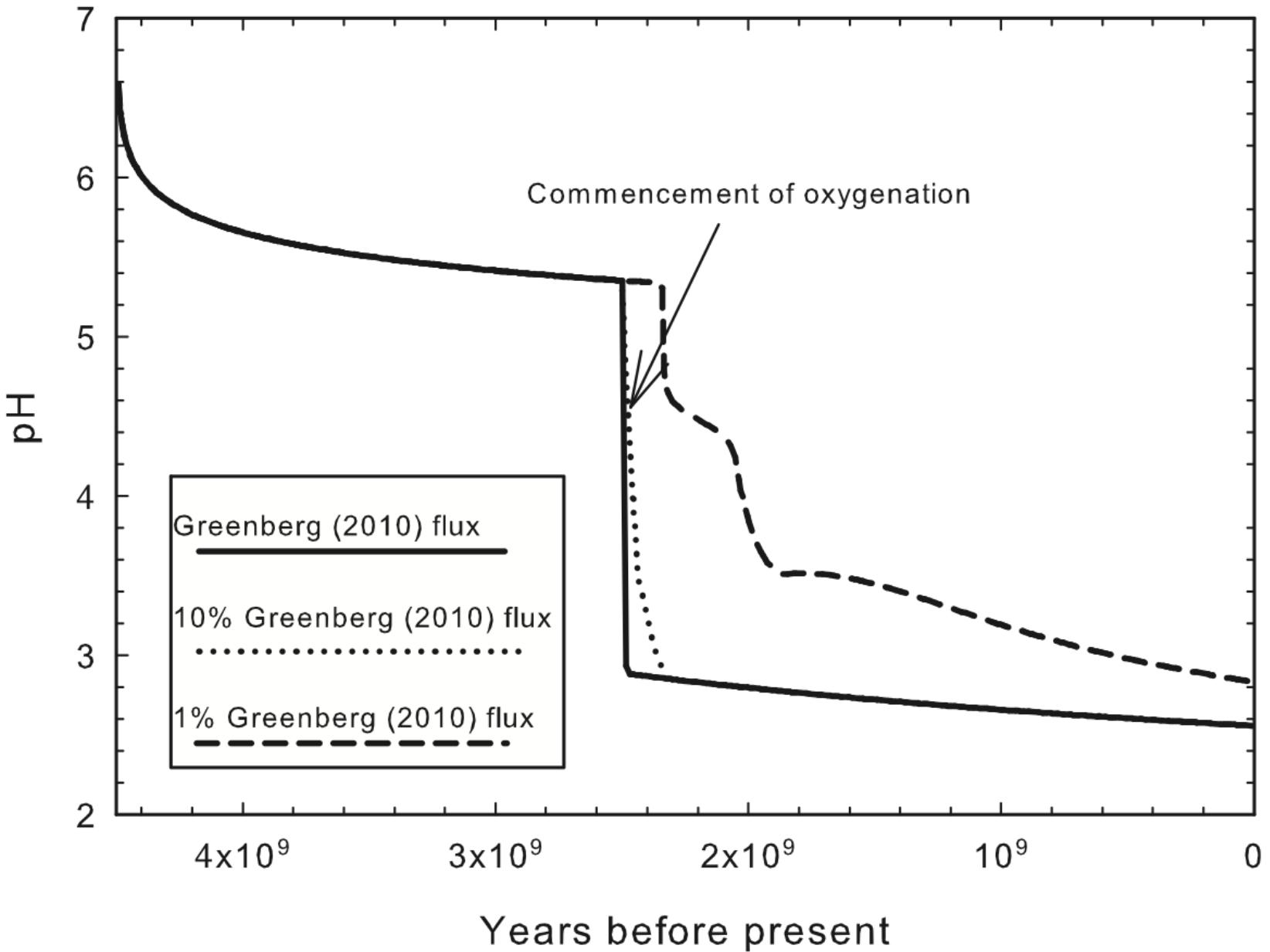
*flux Fe^{2+} could be higher if Europa has less iron in its core.

Hand et al. 2007, 2009

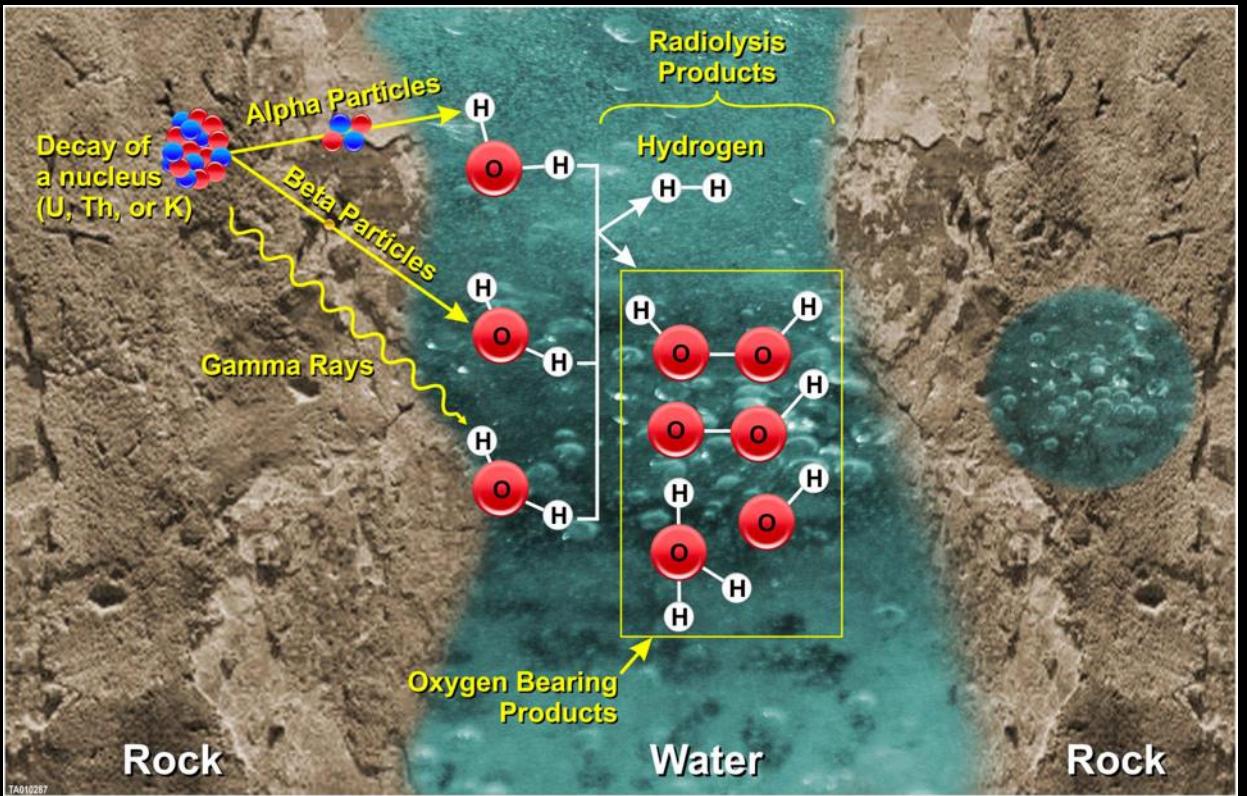
Volcanic hydrothermal flux should scale with Europa's heat:

$$Q = H/c_w \Delta T \quad (\text{Lowell and Dubose 2004})$$

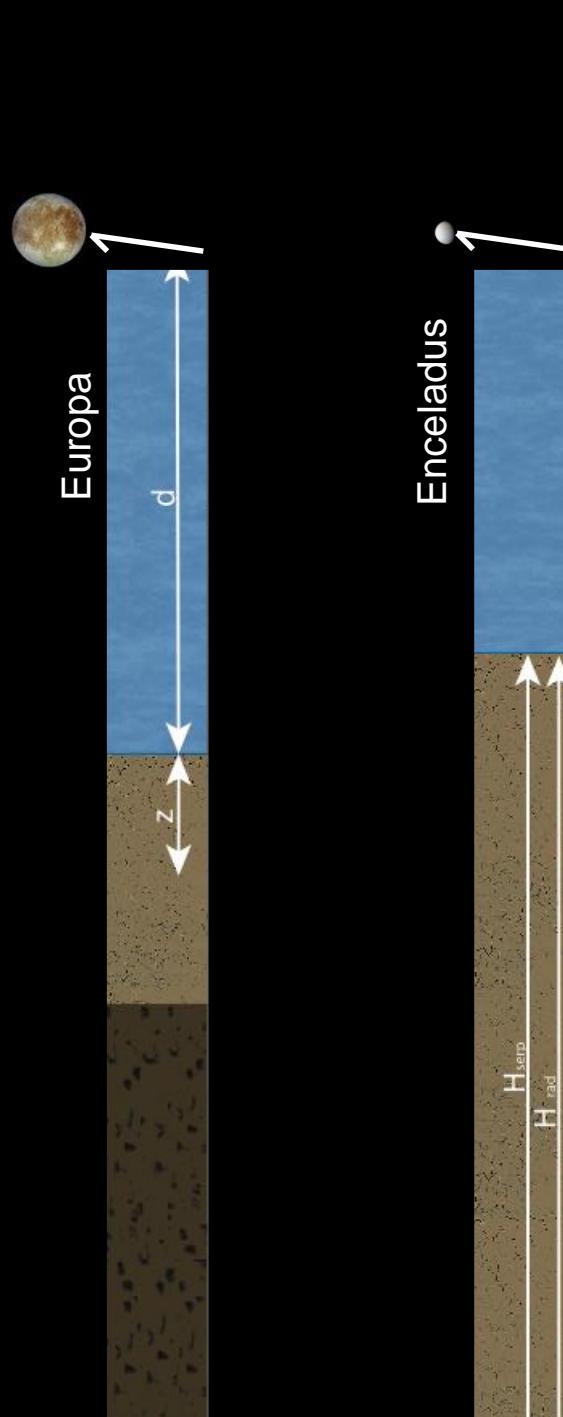
Here, assume $\Delta T=350^\circ\text{C}$ and 2-6 mm H_2 (Holland 2002)



A reducing mantle interface without
vigorous mantle convection

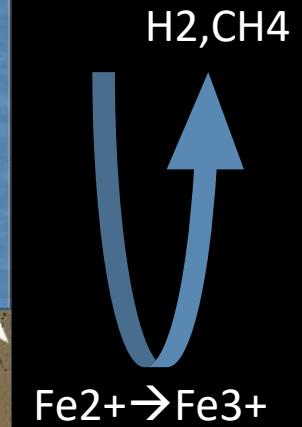


Bouquet et al. 2017



Vance et al. 2007, 2016

Neveu et al. 2014





T. H. Vu, R. Hodyss, M. Choukroun, and P. V. Johnson, 2016

E. C. Thomas, R. Hodyss, T. H. Vu, P. V. Johnson, M. Choukroun, 2017

T. H. Vu, R. Hodyss, P. V. Johnson, M. Choukroun, 2017

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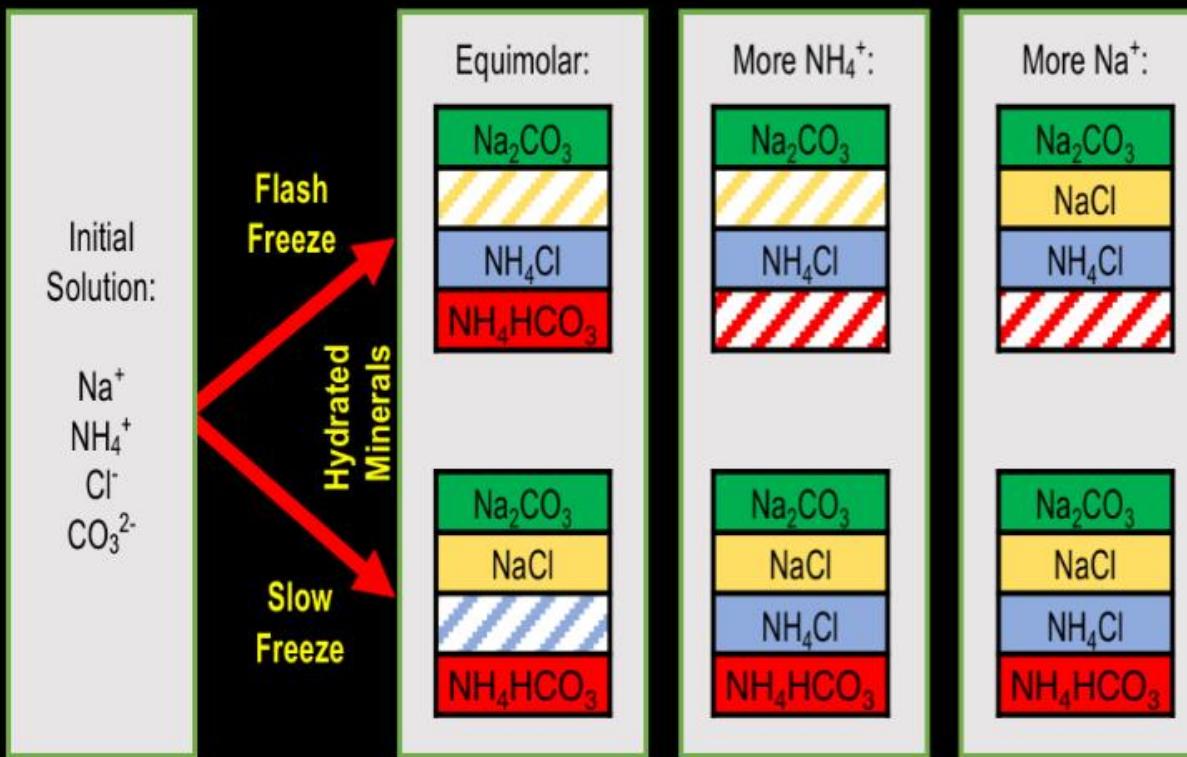
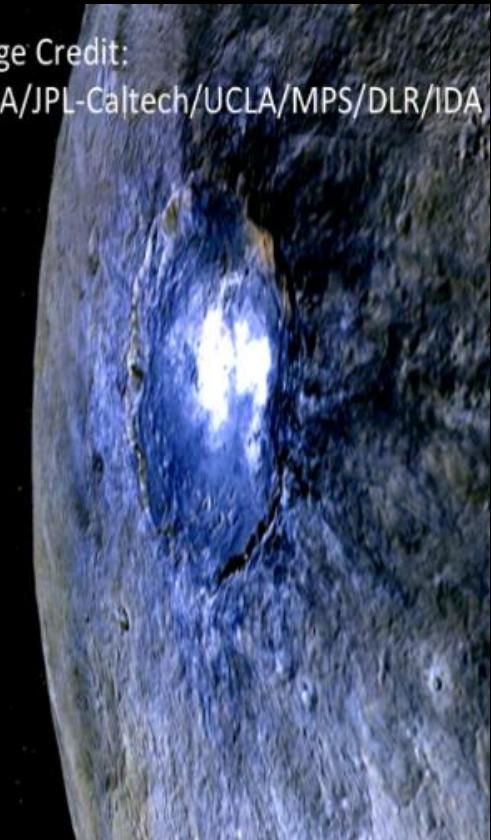
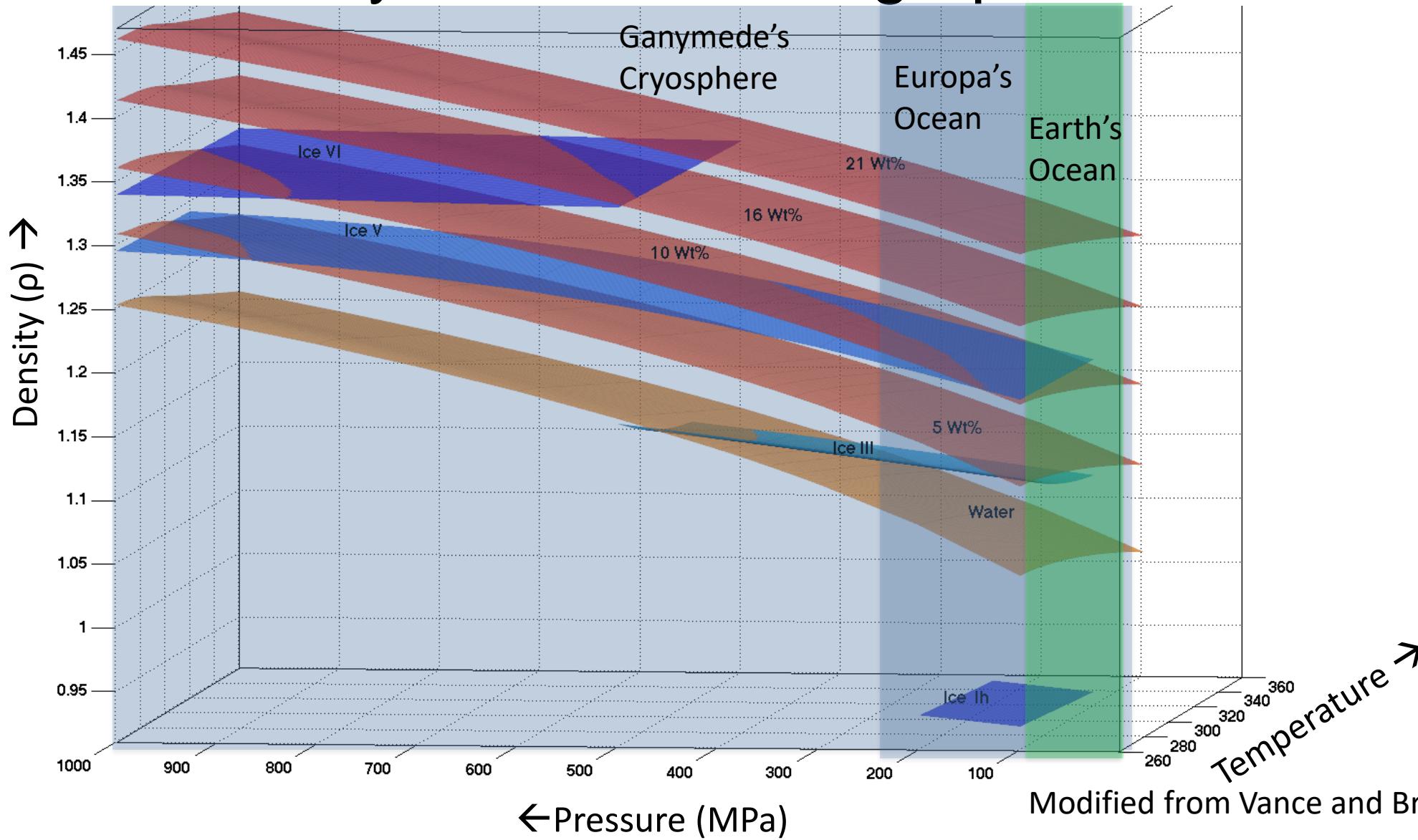


Image Credit:
NASA/JPL-Caltech/UCLA/MPS/DLR/IDA

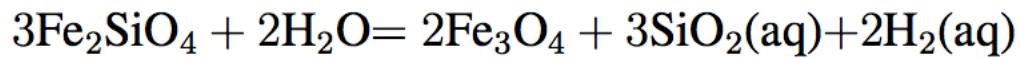


Ceres

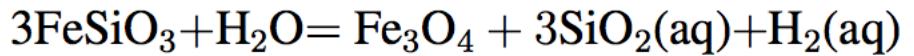
Concentrated MgSO_4 solutions are convectively stable under high-pressure ices



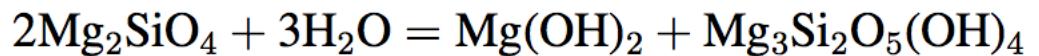
Modified from Vance and Brown 2013.



fayalite + water = magnetite + silica + hydrogen



ferrosilite + water = magnetite + silica + hydrogen.



forsterite + water = brucite + serpentine.

H₂

Heat
41 kJ/mol olivine

Now accounting for estimates of H₂ and O₂ from the Earth System

